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DETERMINATION OF FLOW-FIELD CHARACTERISTICS AROUND GENERALIZED AND SPECIFIC PROTUBERANCES AT MACH NUMBERS 0.60 THROUGH 1.60

T. R. Brice

ARO, Inc.

September 1968

PROPULSION WIND TUNNEL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The work reported herein was done at the request of the National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (MSFC), under Program Area 921E.

The results of tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract F40600-69-C-0001. The test was conducted from May 22 through June 7, 1968, under ARO Project No. PB1877, and the manuscript was submitted for publication on July 30, 1968.

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This technical report has been reviewed and is approved.

Richard W. Bradley
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ABSTRACT

Generalized protuberances in the form of right circular cylinders of 2-, 4-, and 8-in. diameter were mounted on a full-scale Saturn S-IVB panel and tested at various heights for Mach numbers 0.60 through 1.60. Models of the Auxiliary Propulsion Unit and the Rocket Control System protuberances of the Saturn V launch vehicle were also tested. The Reynolds number based on the generalized protuberance diameters varied from 0.25 to 3.0 million. Static and fluctuating pressure levels in the regions around the protuberances were determined, and flow visualization studies were also made. The fluctuating pressure and flow visualization data are not presented in this report.

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NOMENCLATURE

C_p	Local-pressure coefficient, $\frac{p - p_\infty}{q_\infty}$
D	Cylindrical protuberance diameter, in.
h	Vertical distance of orifices above the machined plate, 8-in. protuberance, in.

M_∞	Free-stream Mach number
p	Local pressure, psf
p_{t_∞}	Free-stream total pressure, psf
p_∞	Free-stream static pressure, psf
q_∞	Free-stream dynamic pressure, psf
R	Distance from the center of the protuberance, measured radially, in.
Re/ft	Reynolds number per foot, U_∞/ν_∞
Re_D	Reynolds number based on the generalized protuberance diameter, $\frac{U_\infty D}{\nu_\infty}$
U_∞	Free-stream velocity, ft/sec
u	Local velocity in the boundary layer, ft/sec
x	Vertical distance the cylindrical protuberance extends above the machined plate, in.
y	Vertical distance of boundary-layer probes above the machined plate, in.
δ	Boundary-layer thickness, in.
δ^*	Displacement thickness $\int_0^\delta \left[1 - \frac{\rho u}{\rho_\infty U_\infty}\right] dy$
ν_∞	Free-stream kinematic viscosity, ft^2/sec
ρ	Air density, slugs/ft^3
ϕ	Angular measurement from the model centerline with vertex at the cylindrical protuberance axis, $\phi = 0$ upstream, deg

SECTION I
INTRODUCTION

Current launch vehicles have many and geometrically different external protrusions which affect the flow field in the nearby regions. In these regions the steady and unsteady pressures reach levels which are considerably different from free stream. The purpose of this test was to measure the static pressures and acoustic pressures on and about generalized protuberance shapes and specific protuberance geometries. Accordingly, 2-, 4-, and 8-in.-diam right circular cylinders were mounted on a simulated segment of a full-scale Saturn S-IVB stage and tested as generalized shapes of variable heights. Two protuberances from the S-IVB stage of the Saturn V vehicle were tested for comparison purposes. These were the Auxiliary Propulsion Unit (APU) and Rocket Control System (RCS) protuberances.

The test objectives were achieved by testing the protuberances at Mach numbers from 0.60 through 1.60 for Reynolds numbers of 1.5, 3.0, and 4.5 million per foot (Fig. 1, Appendix).

A secondary objective to obtain flow visualization photographs was realized by injecting an oil-paint pigment mixture of different colors onto the model surface through small orifices upstream of and around the 4-in. protuberance. Flow visualization studies were also made with the APU protuberance. Since pictures in color are required to appreciate the visualization, these photographs are not presented in this report.

SECTION II
APPARATUS

2.1 TEST FACILITY

Tunnel 16T is a variable-density tunnel capable of operating from Mach numbers 0.55 to 1.60. The test section is 16 ft square and has perforated walls which allow continuous operation through the Mach number range with minimum wall interference. More details concerning the tunnel may be found in Ref. 1.

A sketch of the model in the 16T test section is presented in Fig. 2, and photographs of the various configurations are shown in Fig. 3.

2.2 MODEL

The protuberances as shown in Figs. 3 and 4 were mounted on a full-scale segment of the Saturn S-IVB stage. The 30-deg panel with a radius of curvature of 130 in. was supported by two vertical sections of one-half-inch plate, which positioned the centerline of the S-IVB segment 40.75 in. above the tunnel floor. Previous flutter tests utilizing the same basic support fixture in Tunnel 16T have been documented in Refs. 2 and 3.

Modifications to this fixture were made to facilitate installation of the machined panels measuring approximately 3 by 6.3 ft. Provisions were made to install a 2-, 4-, or 8-in. protuberance (Fig. 5a) at the center of the panel. The height of the protuberance could be varied by a drive system which utilized three worm screws linked by a common drive chain to a one-third horsepower electric motor and gear system. Extensions to the 4- and 8-in. protuberances were necessary to provide travel of two protuberance body diameters. Provisions were made to rotate the 8-in. protuberance about its axis.

Two boundary-layer rakes were used to determine the boundary-layer characteristics over the machined panel. Rake 1 was installed on the plate centerline at a point 5.5 in. aft of the machined panel leading edge. When retracted, the rake provided a flush surface with little disturbance to the flow. Rake 2 was fixed on the centerline and sampled the pressure at a point one-half inch forward of the plate aft edge (72.6 in. aft of leading edge). Sketches of the rakes are shown in Fig. 5a.

The two specific protuberances chosen for this test were 0.16-scale models of the APU and RCS. Sketches of these protuberances are presented in Fig. 5b, and photographs of the APU and RCS protuberances installed on the test panel are shown in Fig. 3.

During the latter part of the test, experiments were conducted to develop effective flow visualization techniques in the region near the protuberances. These experiments were performed on the edge of the S-IVB panel, off the machined panel, with a 2-in.-diam fixed protuberance. The technique evolved in these experiments was then used to obtain photographs of the flow around the 4-in. protuberance installed on the machined panel. For all these studies, oil and paint pigment mixtures of various colors were released forward of, around, and behind the protuberance through small orifices. The resulting flow patterns were recorded on color motion pictures and are not included in this report.

2.3 INSTRUMENTATION

The number and locations of steady and unsteady pressure measurements varied from configuration to configuration. The number of static-pressure orifices on the 2- and 4-in. protuberance configurations was 258, and the 8-in. configurations had 272 and 296 static-pressure orifices for the basic and extended versions, respectively. The total number of microphones remained at 122 for all configurations. The arrangement of the orifices and microphones on the panel and on the 8-in. protuberance is shown in Fig. 6. An additional 40 pressures were measured using the two boundary-layer rakes shown in Fig. 5. Those pressures on the aft, fixed rake were measured on the PWT Precision Pressure Balance System. The remaining pressures were measured on electrically driven pneumatic switches with self-contained, differential pressure transducers mounted under the panel (Figs. 3f and g). Eight of these switches, each capable of measuring 48 pressures, were used.

All pressure-transducer signals were converted to digital form and processed by a computer. Pressures from surface orifices were reduced to coefficient form, and those from the boundary-layer rake probes were used to compute local Mach number and velocity ratios through the boundary layer.

The signals from the microphones were conditioned by miniature charge amplifiers mounted within the model and were recorded on magnetic tape.

A linear potentiometer was used to determine the travel of the movable protuberances.

SECTION III
TEST DESCRIPTION

3.1 PROCEDURE

All configurations were tested at Mach numbers from 0.60 through 1.60 and a Reynolds number of three million per foot. The 4-in. protuberance was tested also at a Reynolds number of 1.5 million per foot and the 8-in. protuberance at Reynolds numbers of 1.5 and 4.5 million per foot.

For each tunnel condition the height of the particular protuberance was varied, with steady- and unsteady-pressure measurements recorded consecutively. The height of the 8-in. protuberance was varied from zero to 2.5 protuberance body diameters, and the 2-in. protuberance from zero to 3.5 protuberance body diameters. The 8-in. protuberance configurations had three rows of static orifices mounted on the cylindrical surface of the protuberance (Fig. 6). Rotation of the protuberance by angles of 15 and 60 deg provided measurements at additional locations.

For those test conditions at which boundary-layer data were obtained, measurements on the fixed rake (aft) were recorded only with the forward rake retracted.

3.2 PRECISION OF MEASUREMENTS

The uncertainties associated with maintaining tunnel conditions are estimated as follows:

Mach number, subsonic	±0.005
Mach number, supersonic	±0.010
Total temperature	±5°F
Total pressure	±5 psf

The longitudinal variation of Mach number along the centerline of the test section is not included in the above values and reaches a maximum of ±0.007 at supersonic Mach numbers.

The pressure measurements of the model pneumatic system have been evaluated by measuring a common pressure on all pneumatic switches and on the Tunnel Precision Pressure Balance (PPB) system. The maximum variations are presented below:

M_∞	p_{t_∞}	Δp, psf	p_{t_∞}	Δp, psf
0.60	925	±1.9	2900	±5.8
1.00	757	±4.0	2265	±12.1
1.20	740	±6.6	2205	±19.6
1.60	780	±8.5	-	-

These variations are for the worst cases encountered; generally, the variations were much smaller than indicated.

SECTION IV
RESULTS AND DISCUSSION

Boundary-layer profiles presented in Fig. 7 were determined near the leading and trailing edges of the machined panel, approximately equidistant from the protuberance center. Both Figs. 7a and b show that the rakes were immersed in a very thick boundary layer at the subsonic Mach numbers. This thicker boundary layer was anticipated and emanates from an upflow over the leading edge of the fixture. Boundary-layer thicknesses at sonic and supersonic Mach numbers are 1.5 to 2.0 in. near the front edge and 2.5 to 3.0 in. near the rear edge of the machined panel. The pronounced Reynolds number effect on rake one at Mach number 1.40 is probably due to a disturbed reference pressure, the source of which is not known, and consequently has not been corrected.

The displacement thicknesses as determined from the numerical integration of the velocity profiles are shown in Fig. 8. The theoretical curve is from an equation by Bies (Ref. 4). Transition was assumed to begin 2 ft from the leading edge of the fixture. The aft rake illustrates the separated flow over the panel for Mach numbers less than 0.90. The displacement thicknesses shown for M_∞ = 0.60 and 0.80 were obtained by numerical integration to a point where u is approximately 0.95 U_∞.

Pressure measurements on the stagnation line (ϕ = 0 deg) of the 8-in. protuberance (Fig. 9) show that free-stream stagnation pressure is reached at points 8.5 to 10 in. above the panel for the lower Mach numbers. Pressure measurements at other meridian angles on the protuberance, also shown in Fig. 9, indicate that separation on the protuberance occurs at more than 90 deg for M_∞ = 0.60 but occurs at angles near 60 deg for Mach numbers greater than 0.60. The data at the 90-deg meridian angle at Mach number 0.60 exhibited variations which flow studies showed to be an upflow onto the protuberance cap. The large variations on and near the bottom of the stagnation line of the protuberance are indications of a separation and reverse flow region at the protuberance base, which were confirmed by the flow-visualization studies.

The pressure coefficients in Fig. 10 were determined from measurements on the panel centerline, forward and aft of the 8-in. protuberance at various protuberance heights. Here again the effect of the reverse flow region at the base of the protuberance is apparent, more so at the supersonic Mach numbers. For Mach numbers below 1.40 the limit of the upstream disturbance is uncertain but is approximately three diameters for Mach numbers 1.40 and 1.60, with the protuberance fully extended.

The centerline distributions for the 2-in. protuberance shown in Fig. 11 better determine the upstream influence. For the subsonic Mach numbers the effect of the protuberance extended two diameters is apparent up to 10 diameters upstream. The supersonic Mach numbers indicate disturbance to four diameters upstream.

The effect of Reynolds number upon the centerline measurements for Mach numbers 0.60 and 1.40 is shown in Figs. 12 and 13. A comparison of the centerline pressure coefficients for the 8-in. protuberance is shown in Fig. 12 for Reynolds numbers of 1.5 and 4.5 million per foot. For differences in unit Reynolds number (Fig. 12), variations in the centerline distributions occur downstream for subsonic Mach numbers and upstream for the supersonic Mach numbers.

Comparisons of the three protuberance sizes at a Reynolds number of three million per foot are shown in Fig. 13. As in Fig. 12, differences in pressure distributions with changing protuberance Reynolds number are more noticeable aft of the protuberance for the subsonic case, with slight differences upstream for supersonic Mach numbers.

The centerline distributions of Fig. 14 are for the APU and RCS protuberances. The APU protuberance disturbs the upstream regions up to 24 in. forward of the protuberance centerline reference, and the RCS disturbs the upstream field approximately 8 in.

The constant pressure coefficient contours of Figs. 15 and 16 are presented to display the pressure fields around the generalized protuberances. The contour for the 8-in. protuberance in Fig. 15 is useful in determining minute gradients close to the protuberance because of the spacing of the orifices and relative protuberance size. The 2-in. protuberance is useful in determining the extent and degree of disturbance away from the protuberance. The radial measurements are plotted using a logarithmic scale. This method emphasizes the field near the protuberance and does not distort the circular body shape of the generalized protuberances. The isoline patterns change considerably for increasing Mach numbers, especially when shocks form in front of the protuberance.

The isoline patterns for the APU and RCS are shown in Figs. 17 and 18. The peculiar geometry of the APU and RCS creates flow patterns which are not present on the generalized protuberances. The centers of coordinates (R = 0) on the APU and RCS are shown in Fig. 5b. The protuberances were not shown on the isoline figures because of their distorted images in the logarithmic coordinate system.

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1. Test Facilities Handbook (Seventh Edition). "Propulsion Wind Tunnel Facility, Vol. 5." Arnold Engineering Development Center, July 1968.

2. Perkins, T. M. "Aeroelastic Stability of an Array of Full-Scale Panels from the Saturn S-IVB Stage at Transonic Mach Numbers." AEDC-TR-67-9 (AD807312), February 1967.

3. Perkins, T. M. "Flutter Test of an Array of Full-Scale Panels from the Saturn S-IVB Stage at Transonic Mach Numbers." AEDC-TR-68-30 (AD827913), February 1968.

4. Bies, D. A. "A Review of Flight and Wind Tunnel Measurements of Boundary Layer Pressure Fluctuations and Induced Structural Response." NASA CR-626, October 1966.

APPENDIX
ILLUSTRATIONS

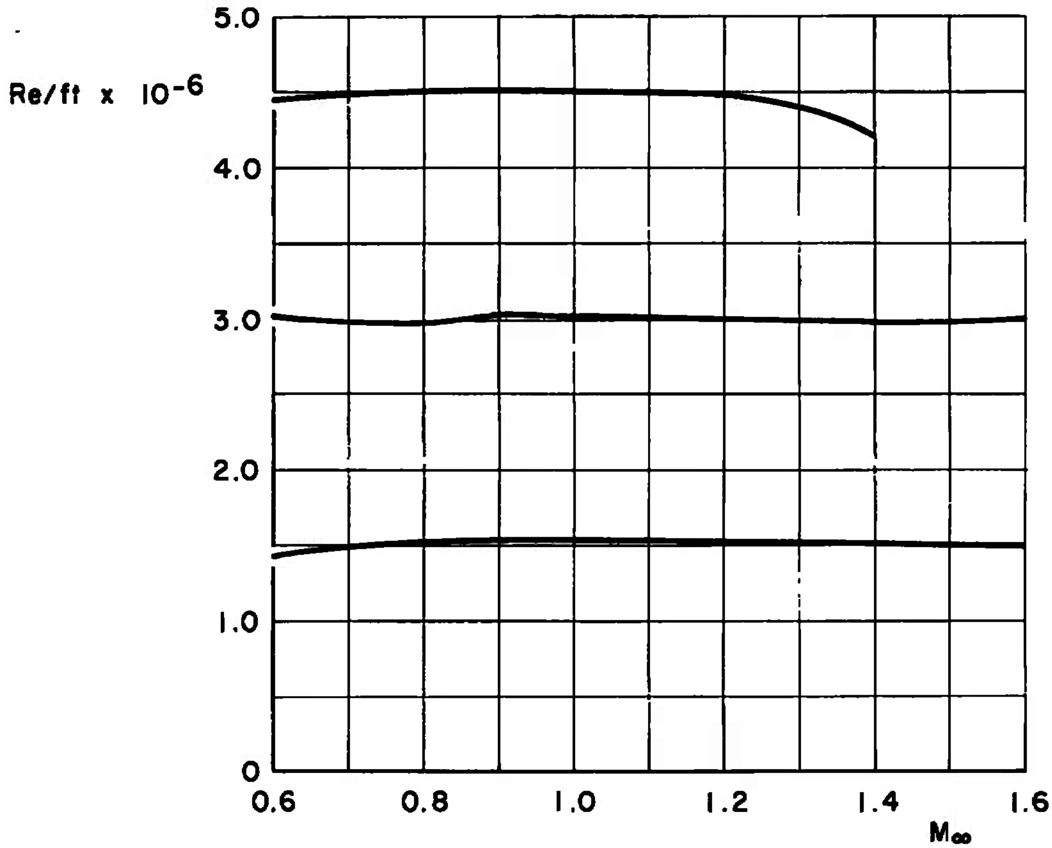


Fig. 1 Reynolds Number Levels for the Mach Number Range

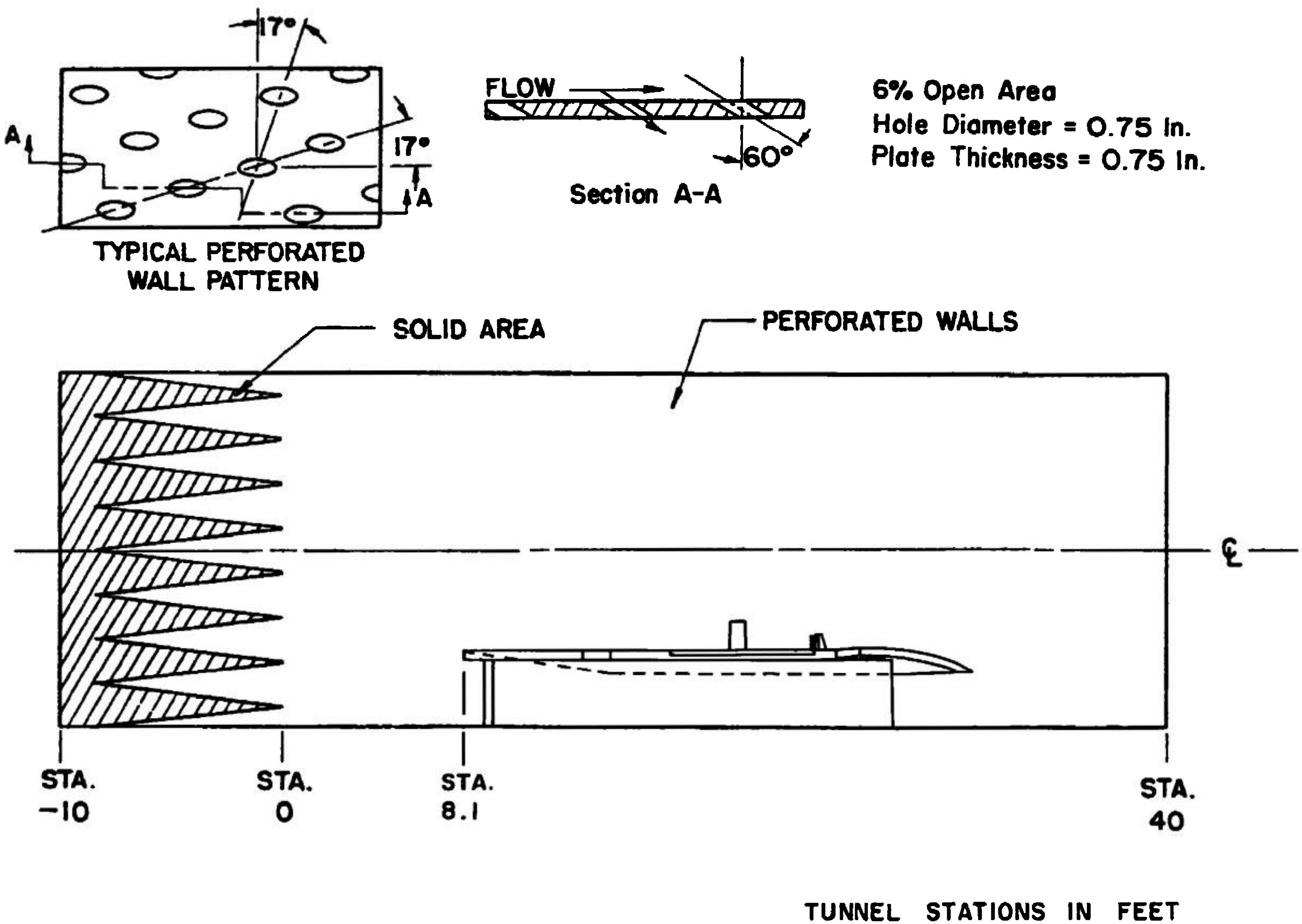
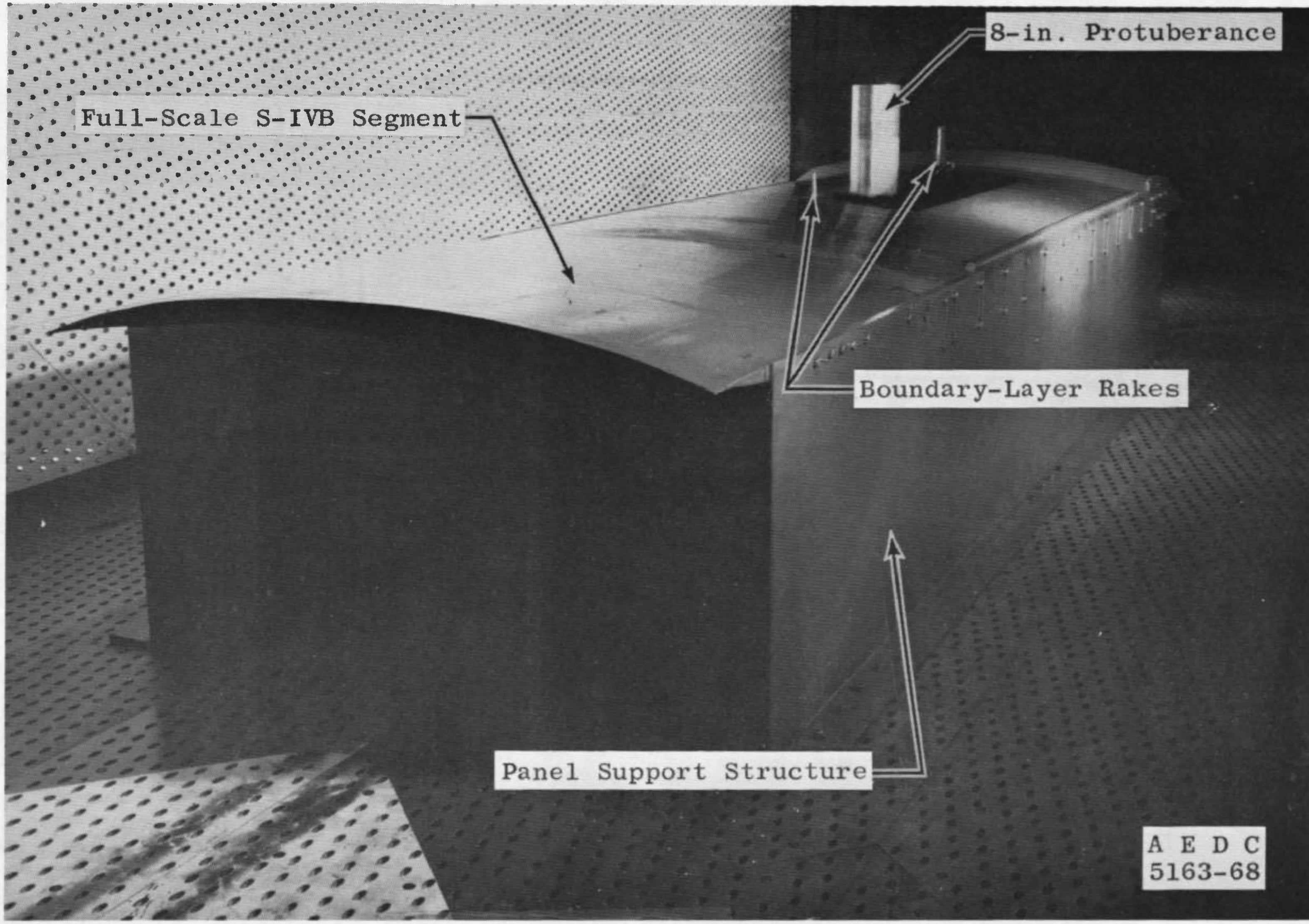
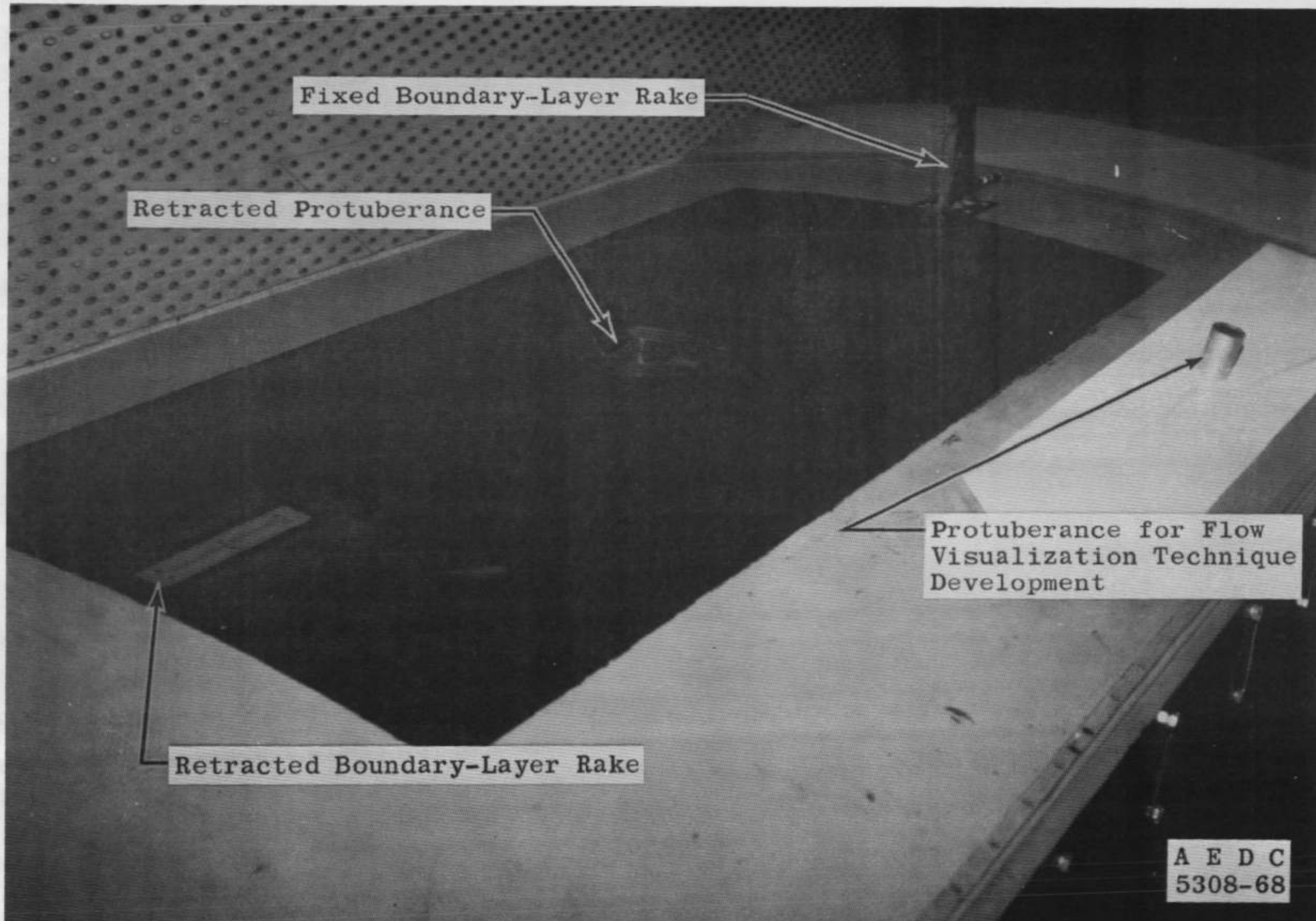


Fig. 2 Installation Sketch of the Model in 16T

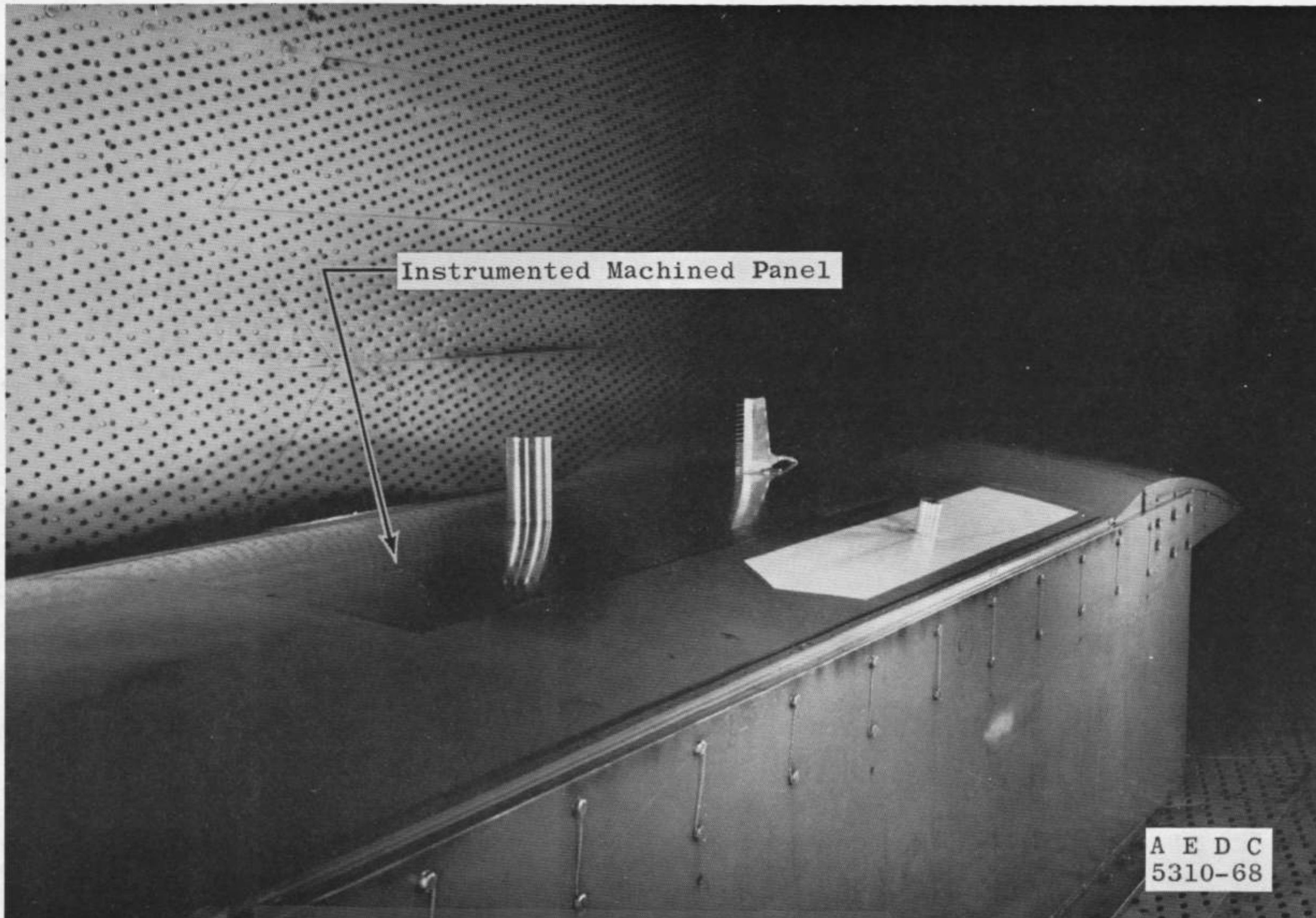


a. Overall View

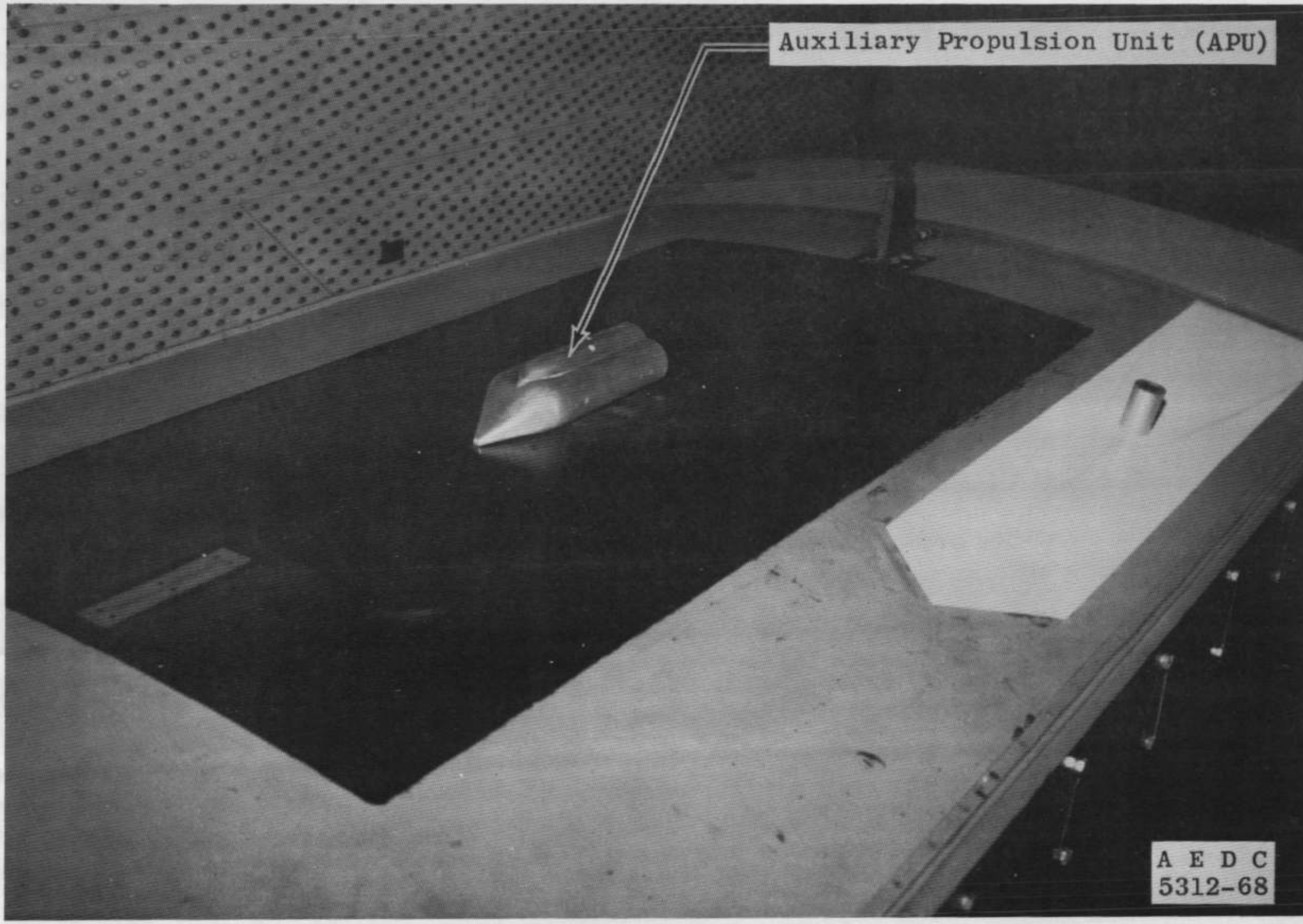
Fig. 3 Installation Photographs of the Model in 16T



b. Machined Panel with the Protuberance and Forward Rake Retracted
Fig. 3 Continued

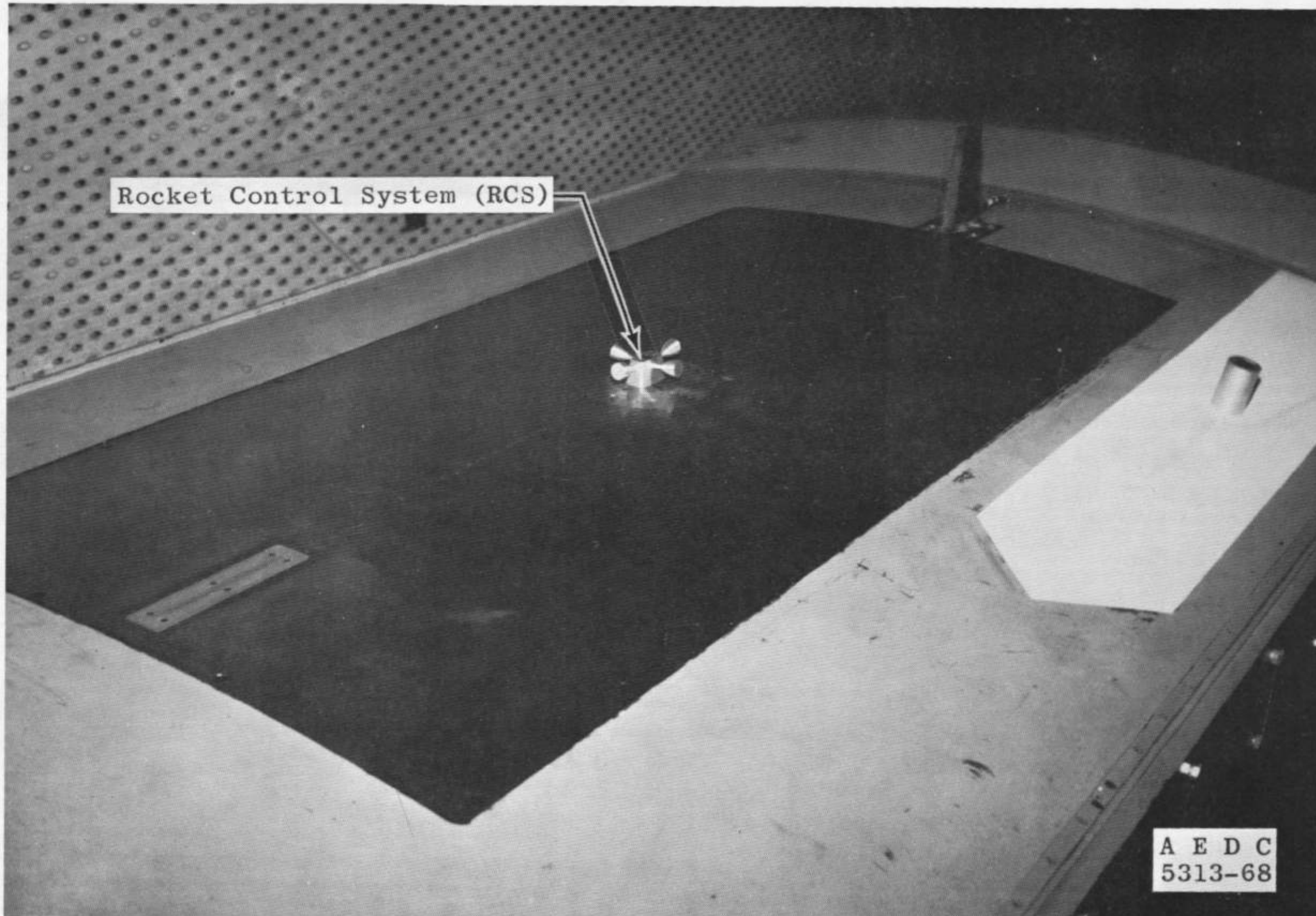


c. 8-in. Protuberance Extended
Fig. 3 Continued

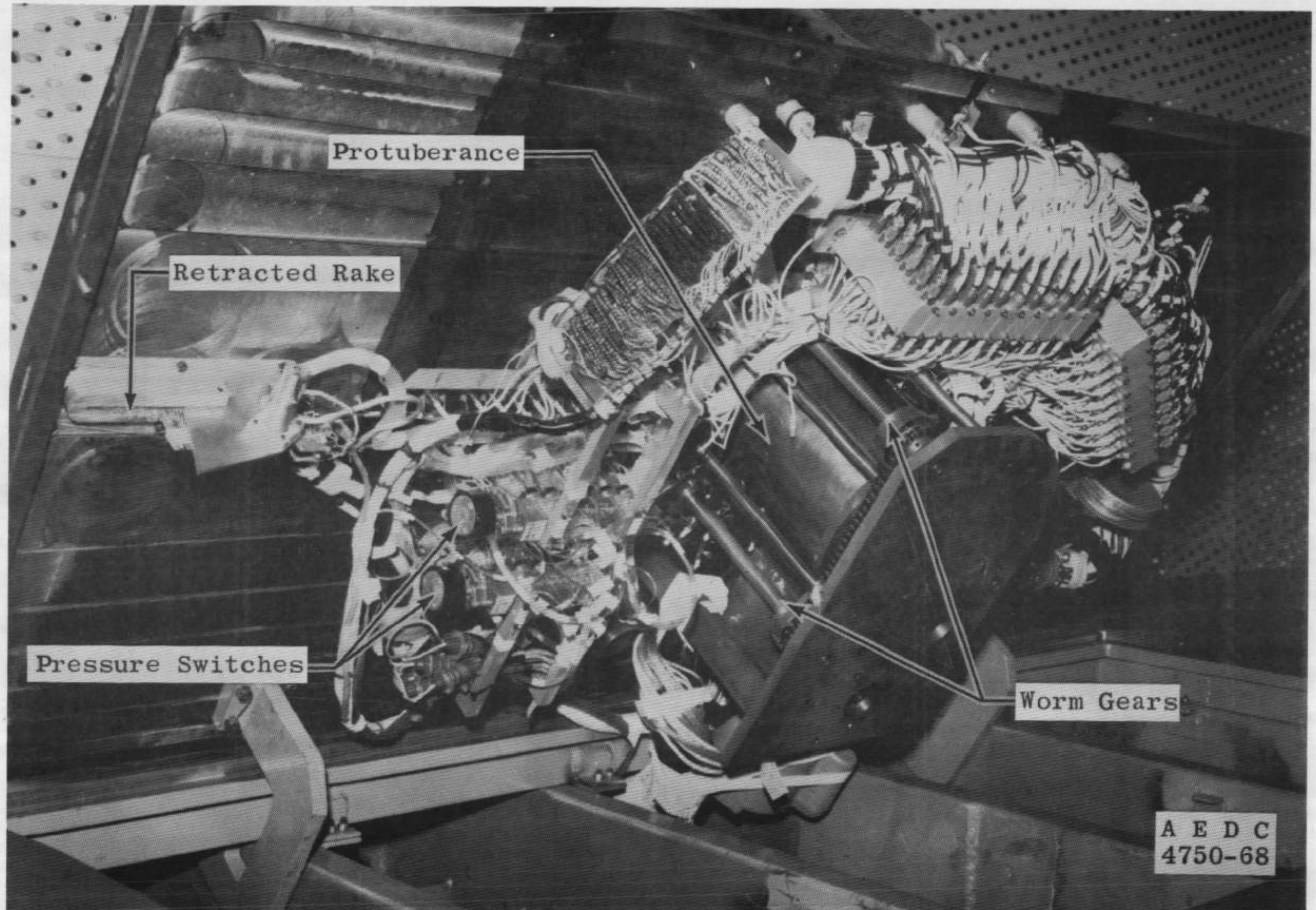


d. Auxiliary Propulsion Unit Installed

Fig. 3 Continued

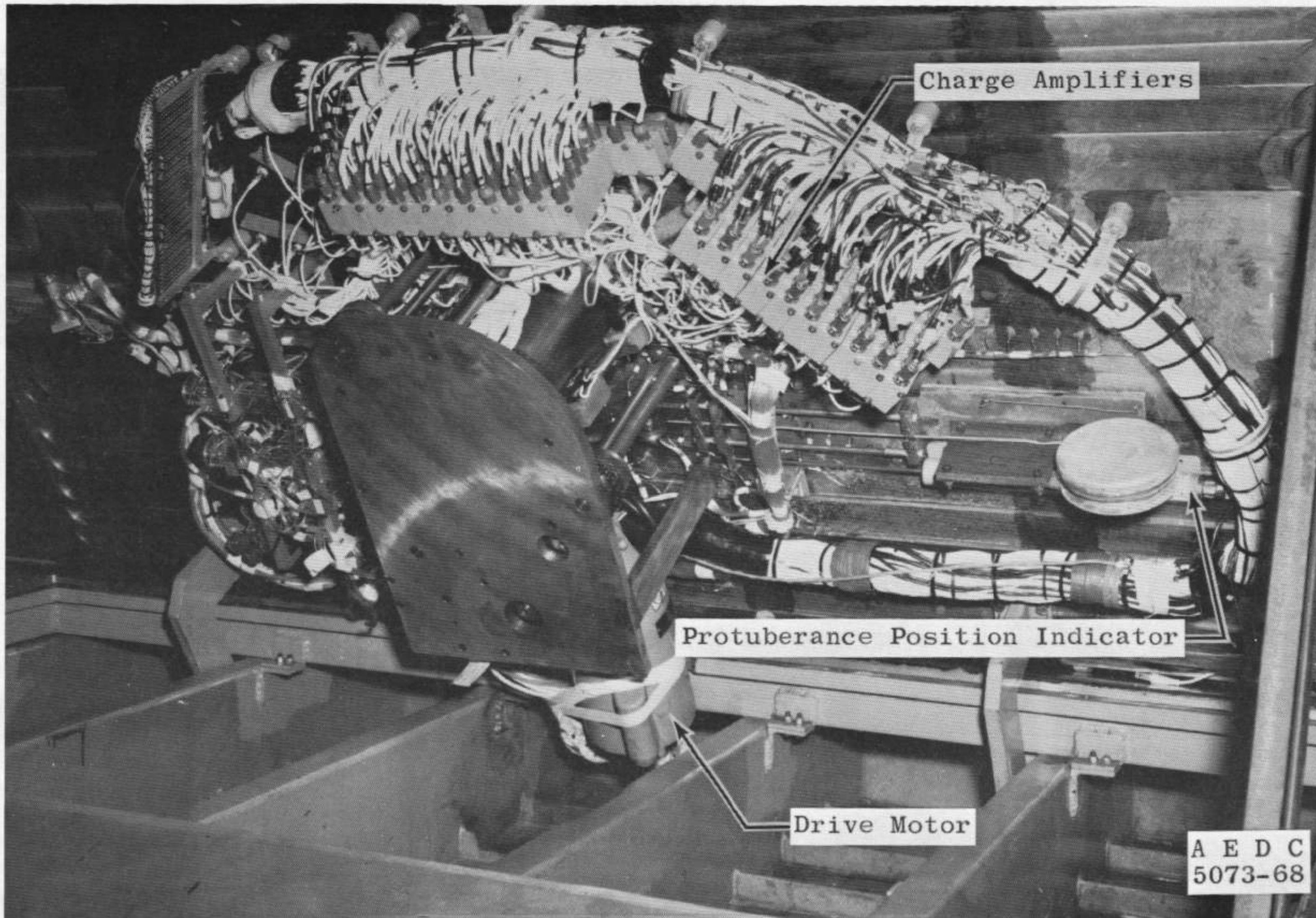


e. Rocket Control System Installed
Fig. 3 Continued



f. Underside of Panel, Looking Aft

Fig. 3 Continued



g. Underside of Panel, Looking Forward
Fig. 3 Concluded

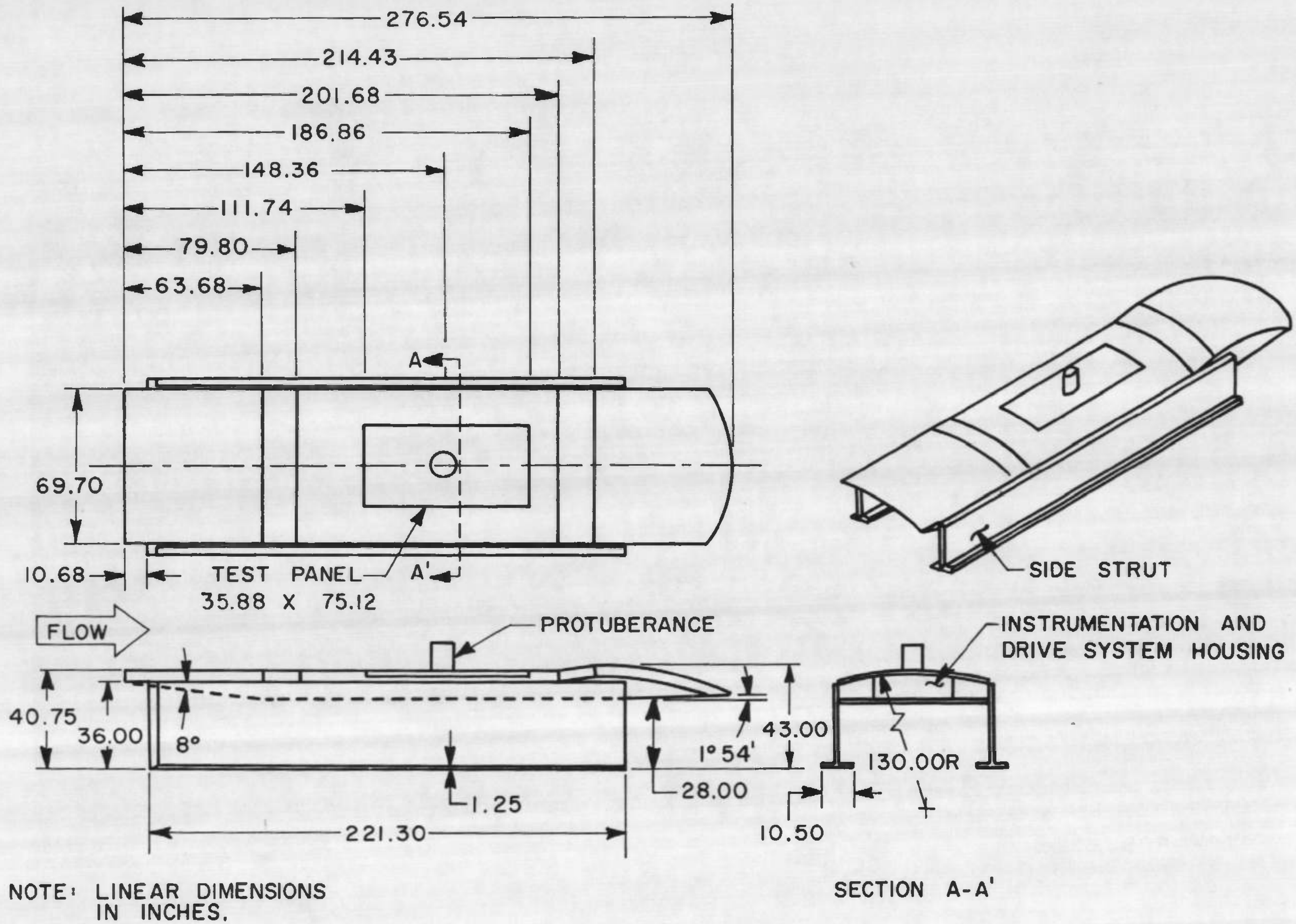
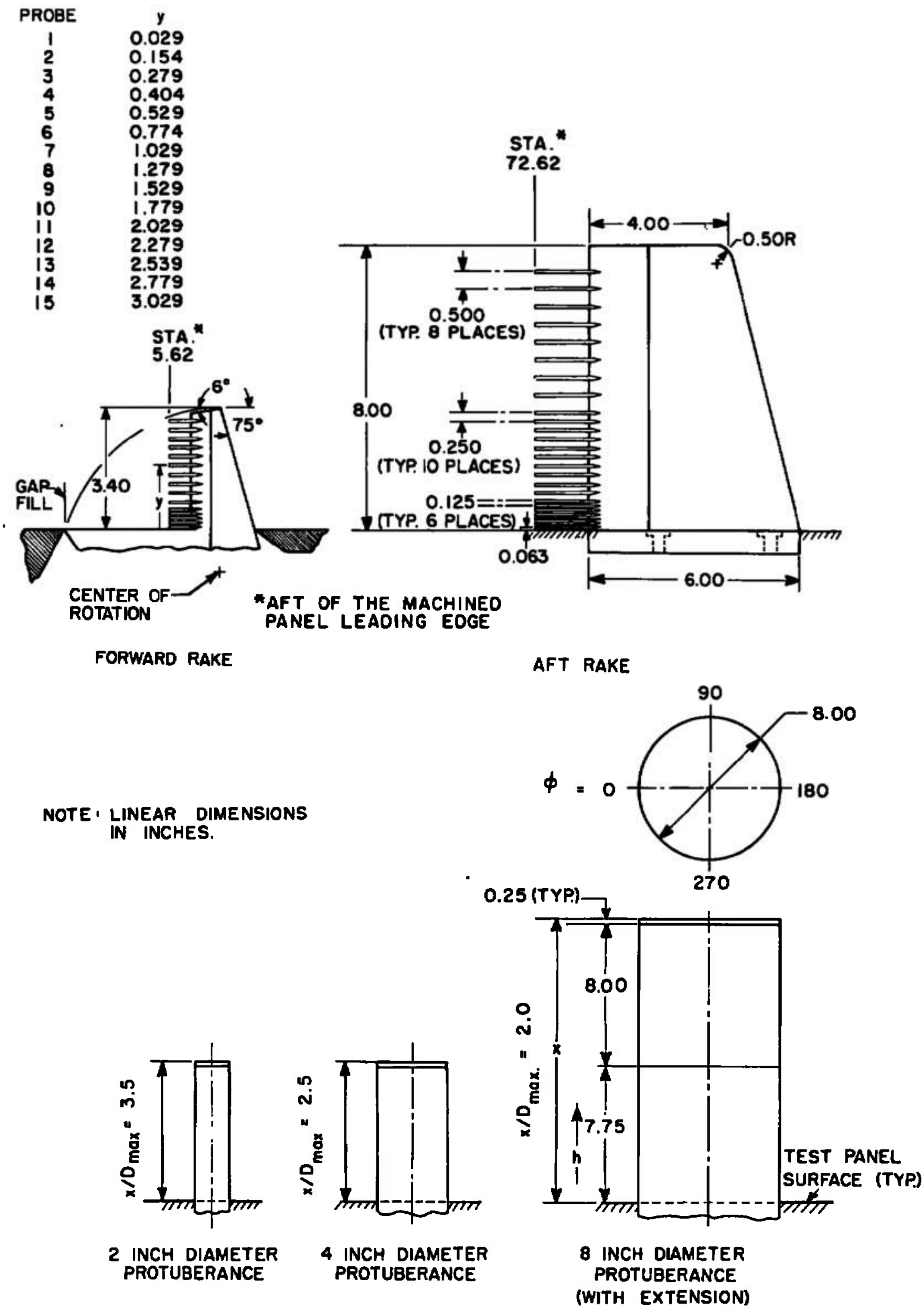
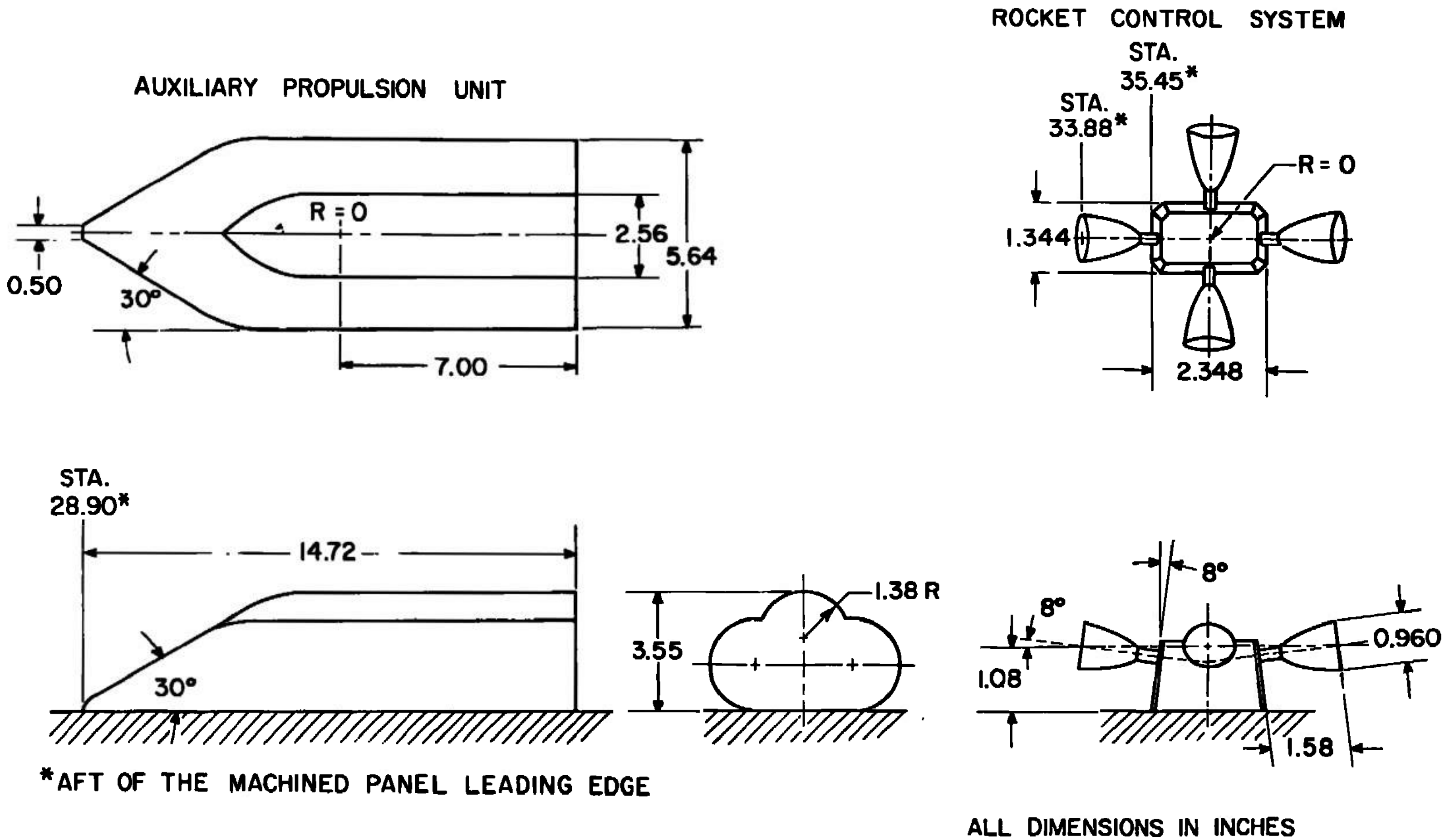


Fig. 4 Sketch of the Model



a. Rakes and Generalized Protuberances

Fig. 5 Details of the Protuberances and Boundary-Layer Rakes



b. Specific Protuberances, Auxiliary Propulsion Unit and Rocket Control System
Fig. 5 Concluded

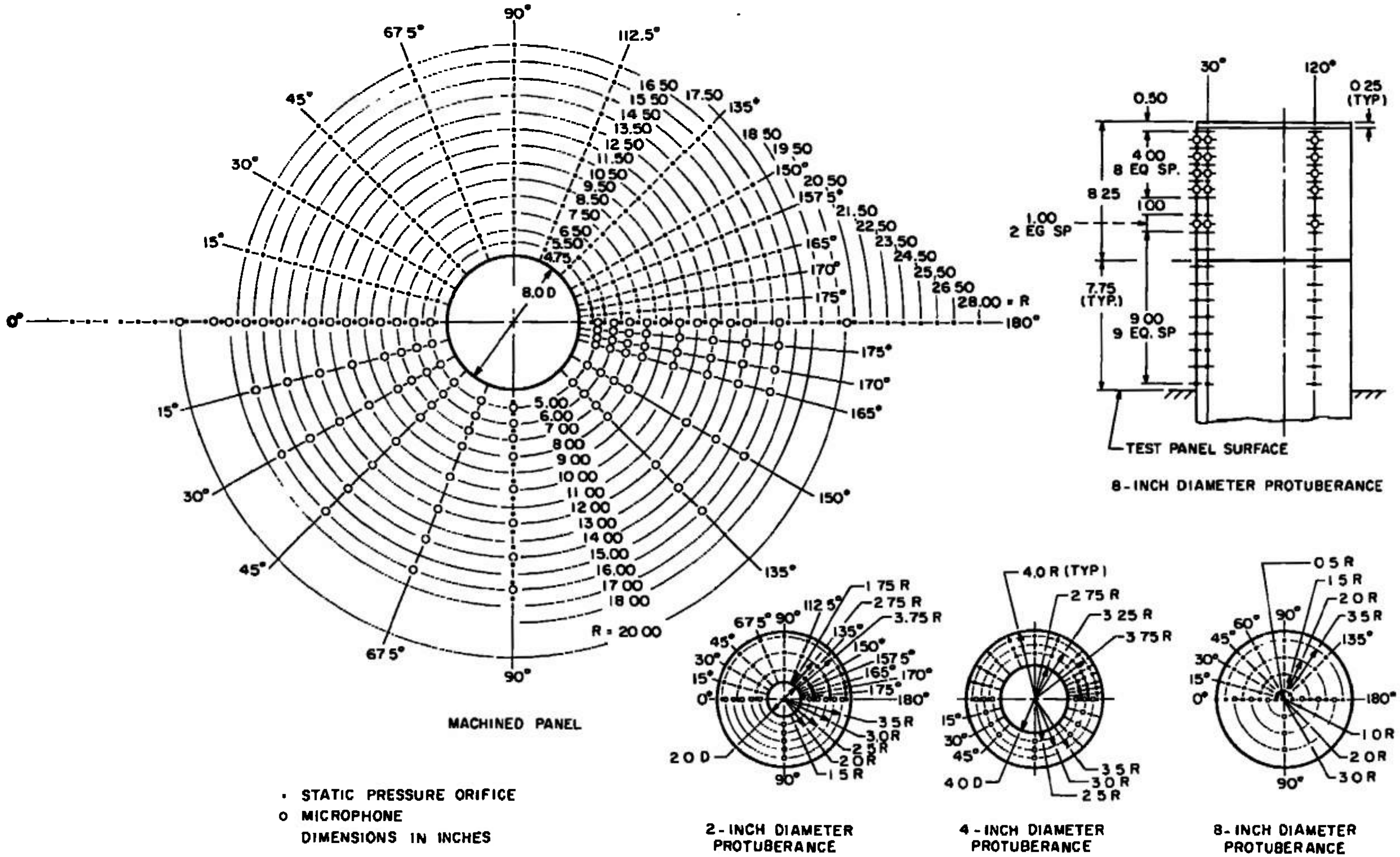
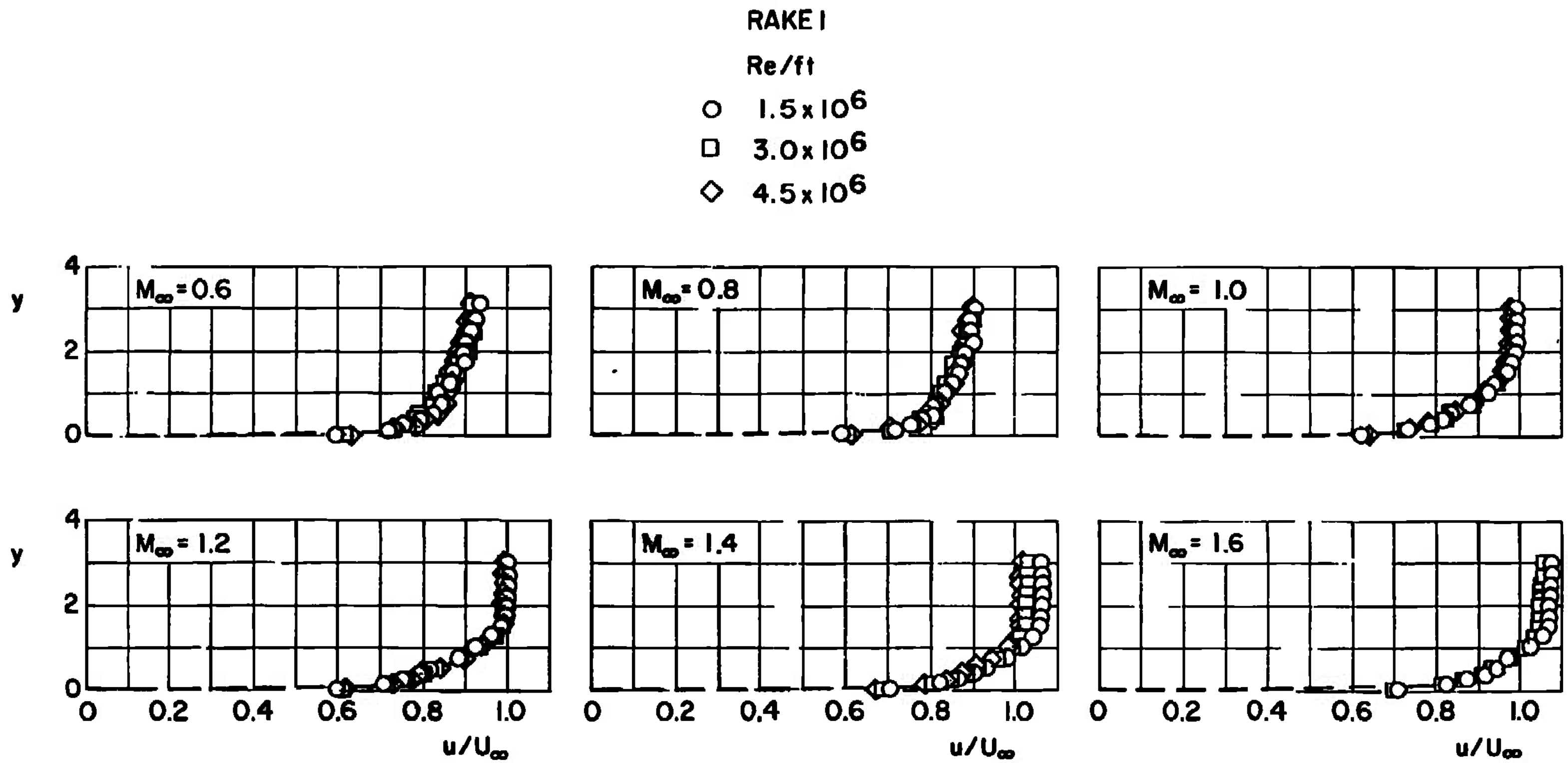
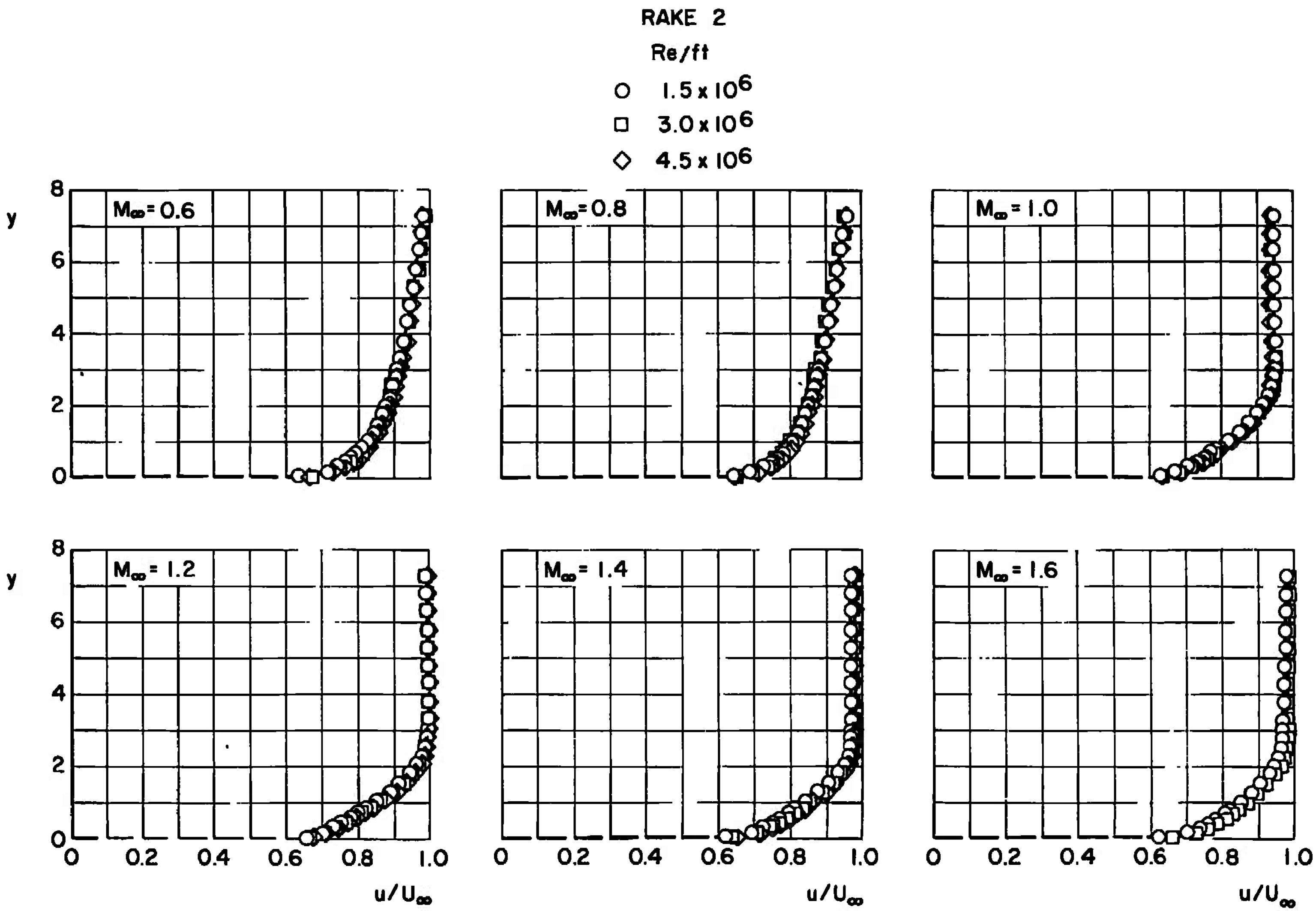


Fig. 6 Orifice and Pressure-Transducer Arrangements



a. Forward Rake

Fig. 7 Boundary-Layer Velocity Profiles



b. Aft Rake
Fig. 7 Concluded

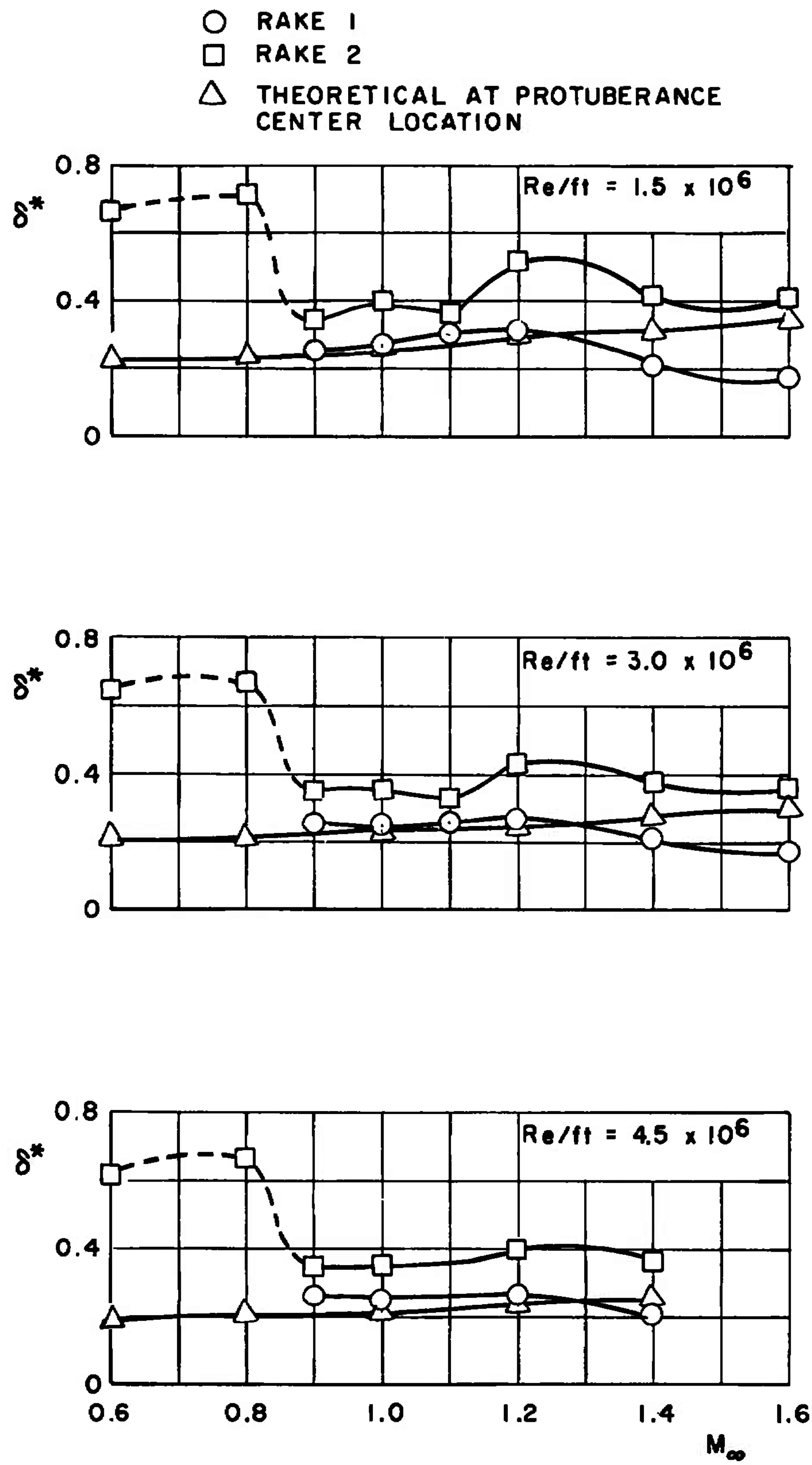
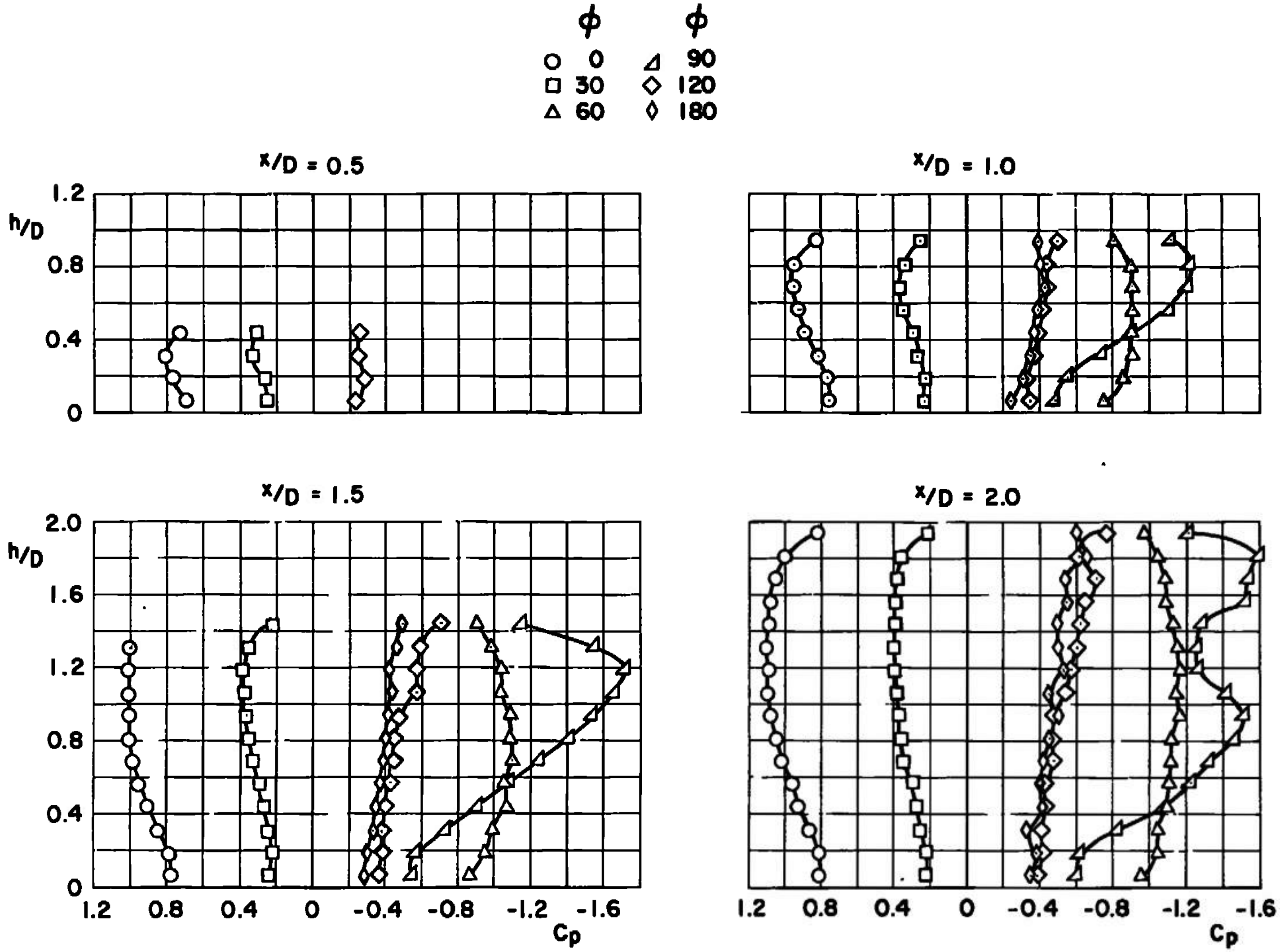
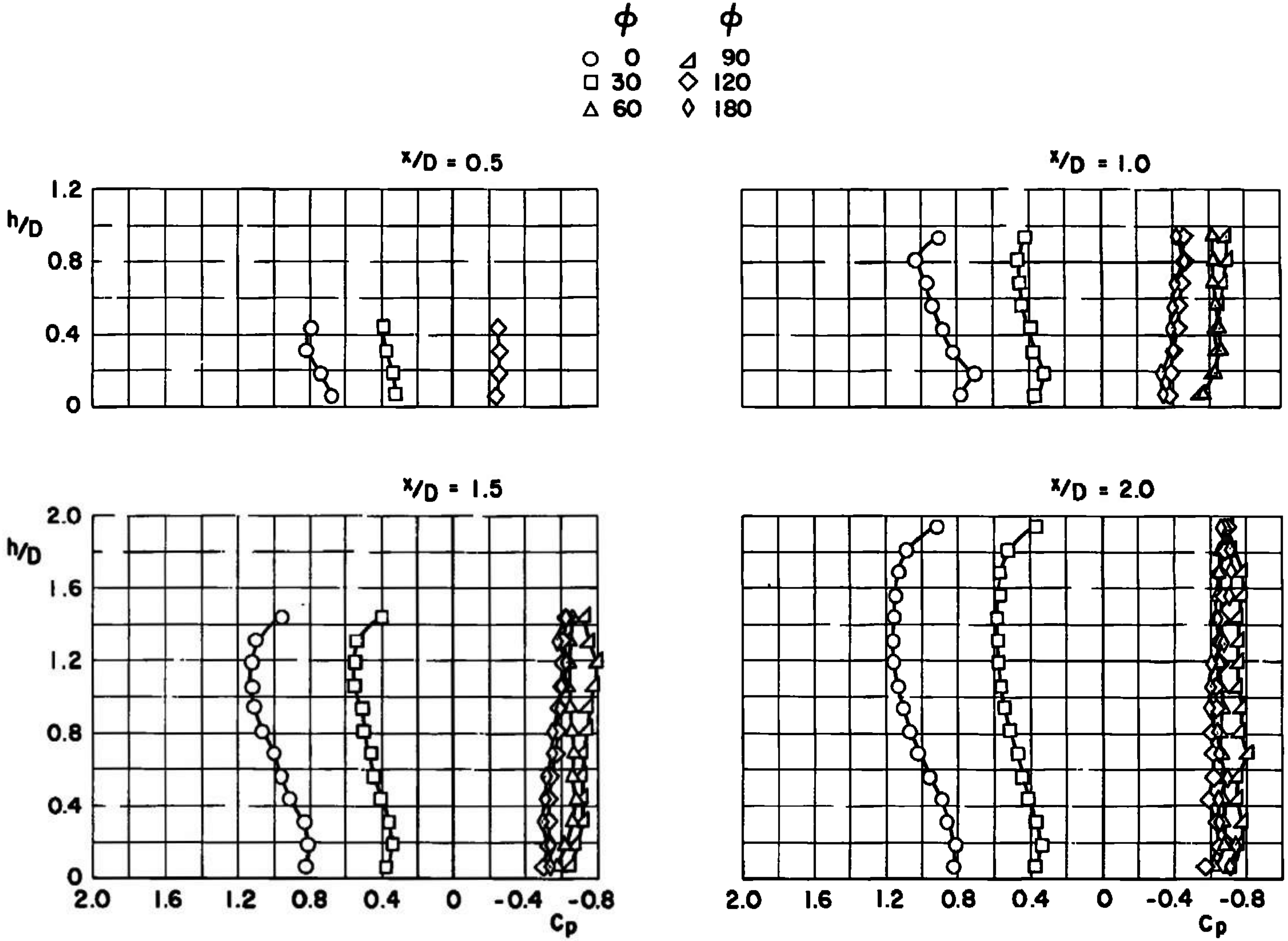


Fig. 8 Variation of Displacement Thicknesses with Mach Number



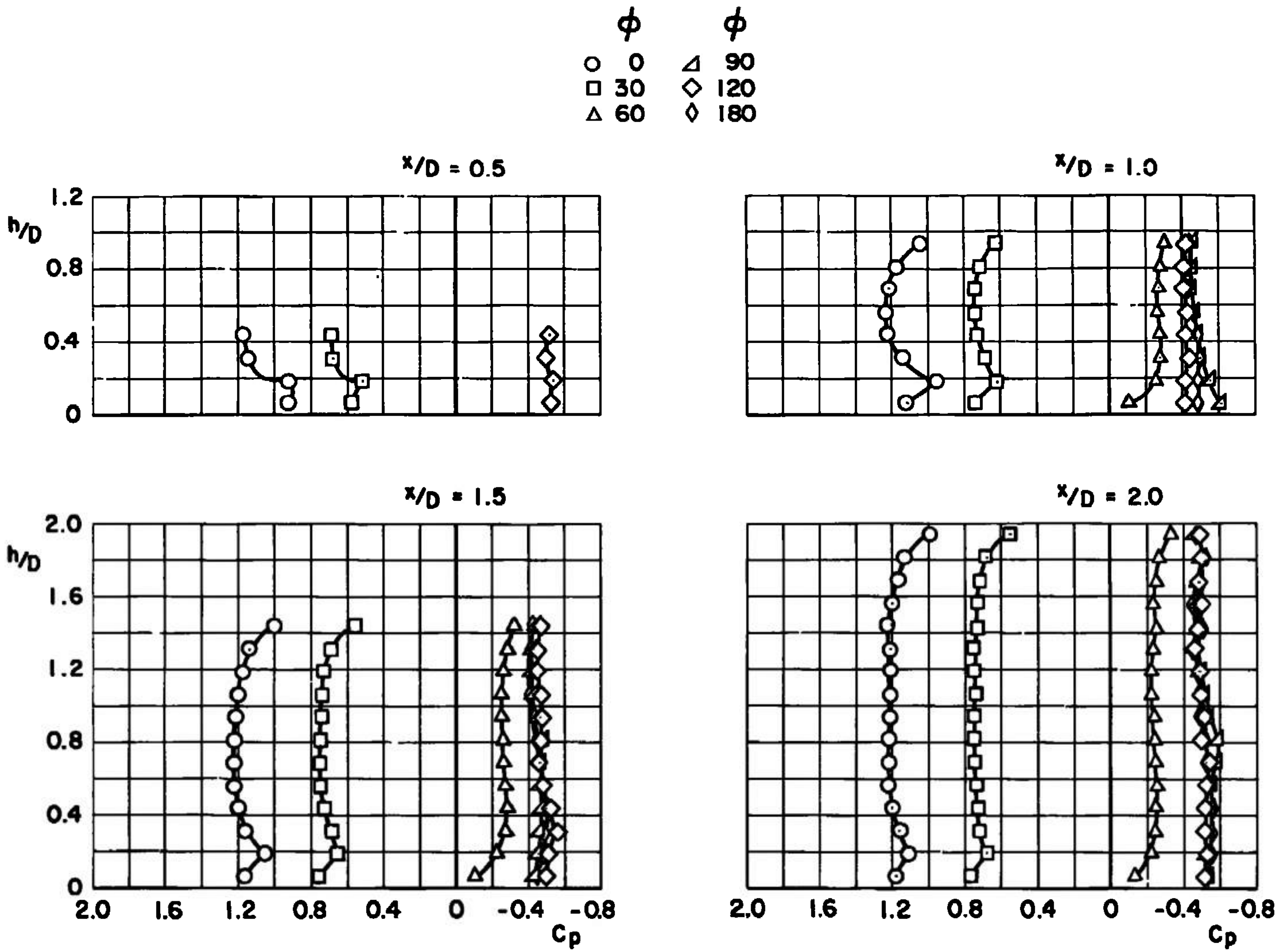
a. M_{∞} – 0.60

Fig. 9 Pressure Coefficients as Measured at Six Angular Stations on the 8-in. Protuberance



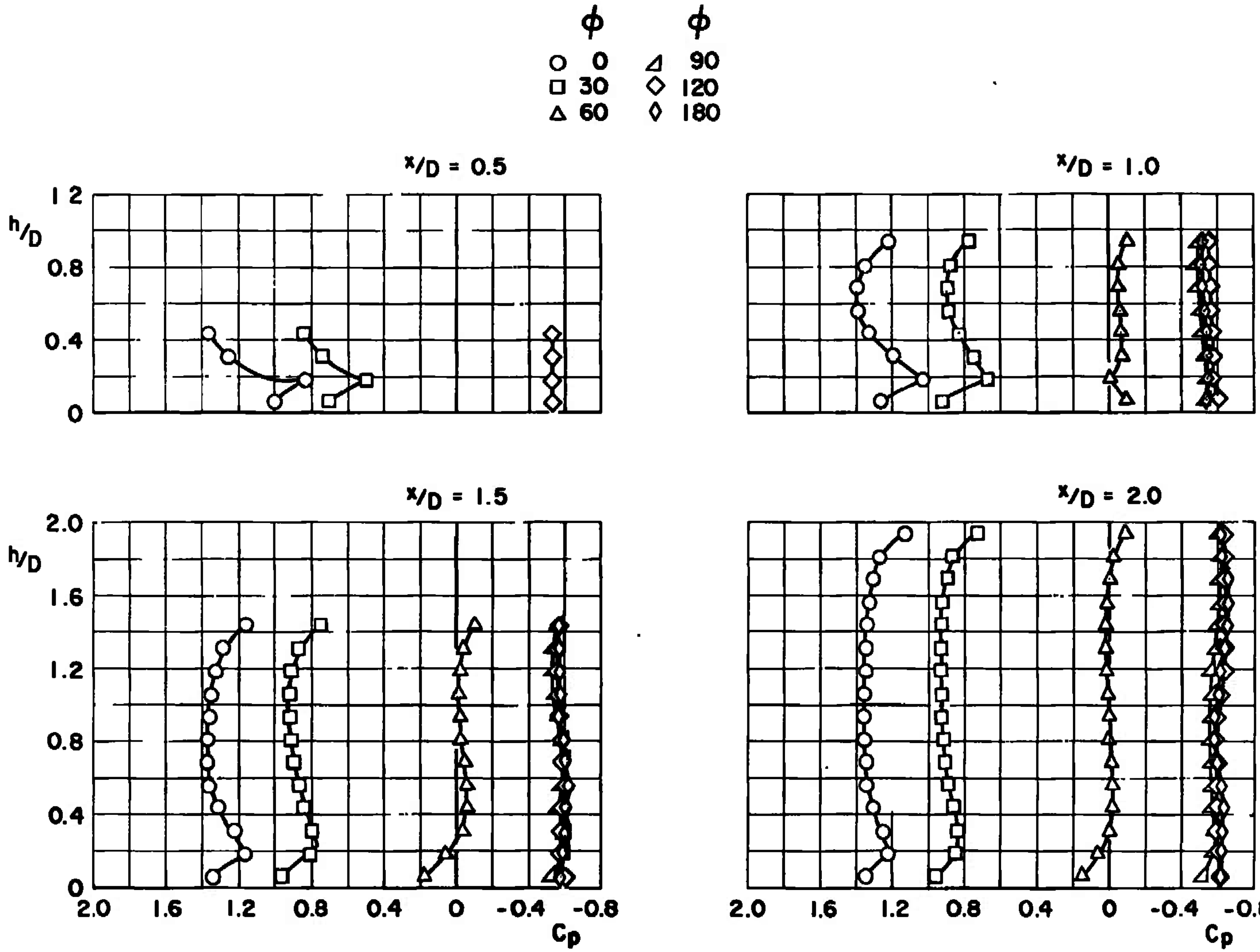
b. $M_\infty = 0.80$

Fig. 9 Continued

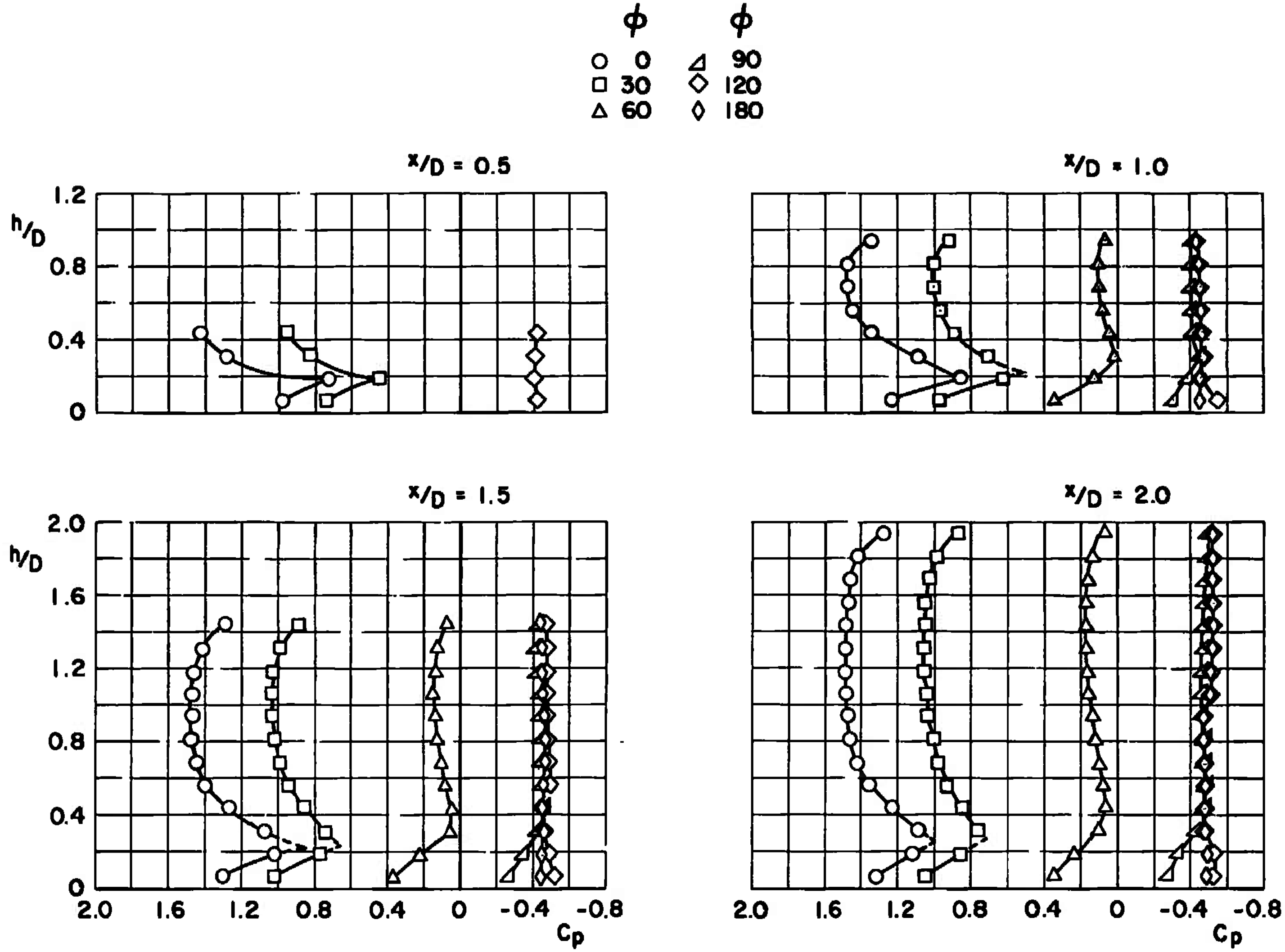


c. $M_\infty = 1.00$

Fig. 9 Continued

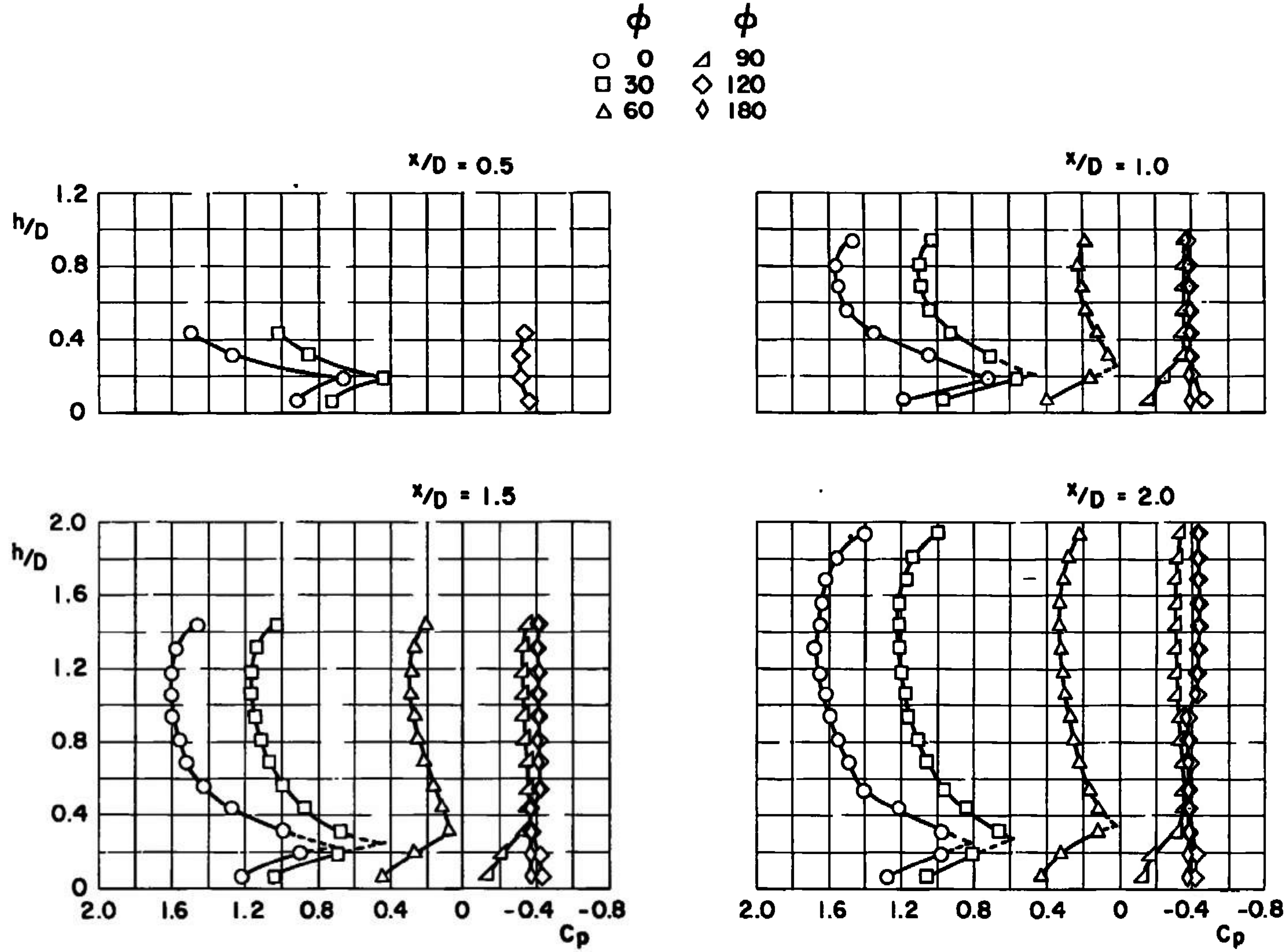


d. M_∞ = 1.20
Fig. 9 Continued



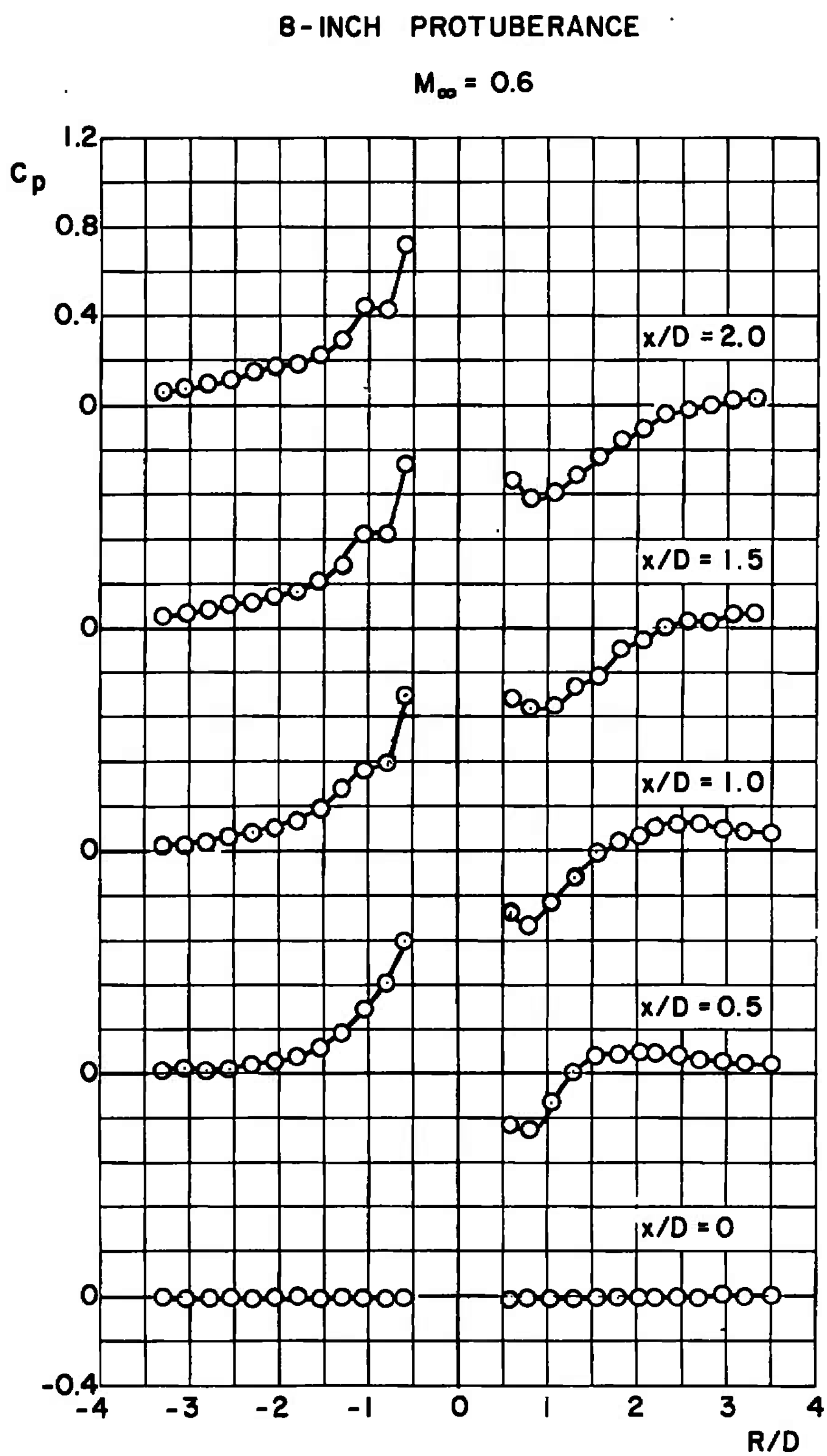
e. $M_\infty = 1.40$

Fig. 9 Continued



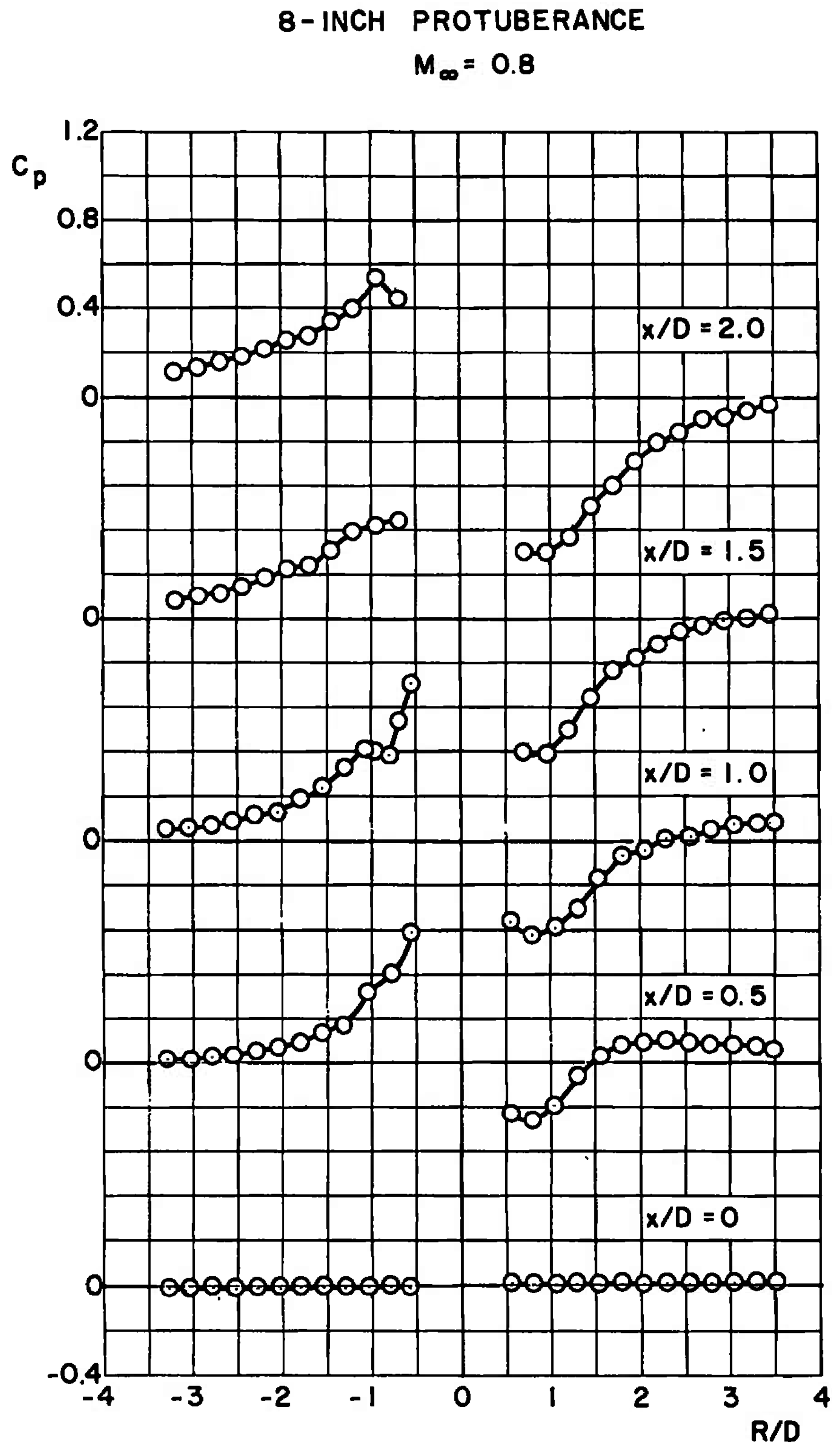
f. M_∞ = 1.60

Fig. 9 Concluded

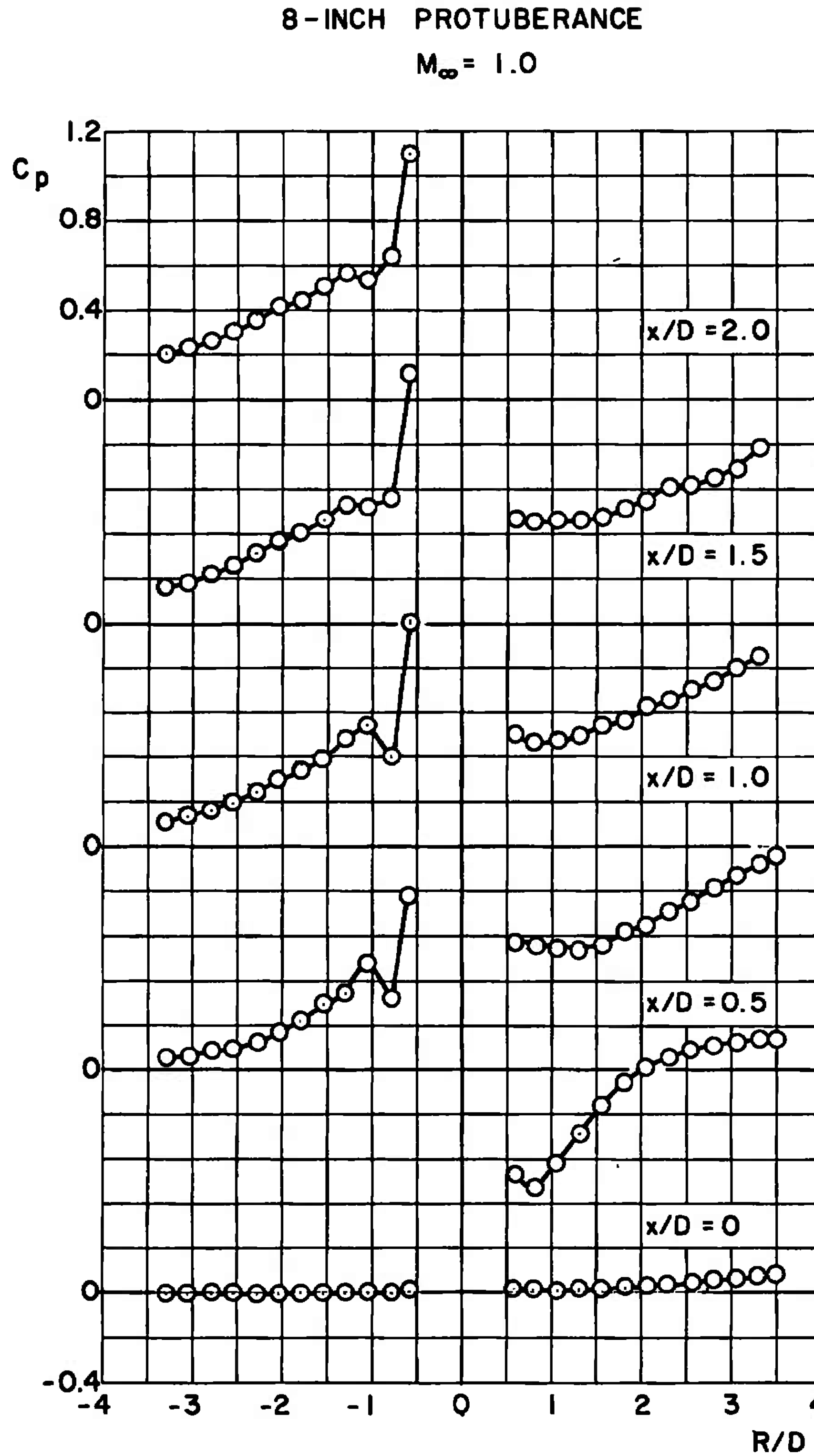


a. M_∞ = 0.60

Fig. 10 Variation of the Test Panel Centerline-Pressure Coefficients for the 8-in. Protuberance

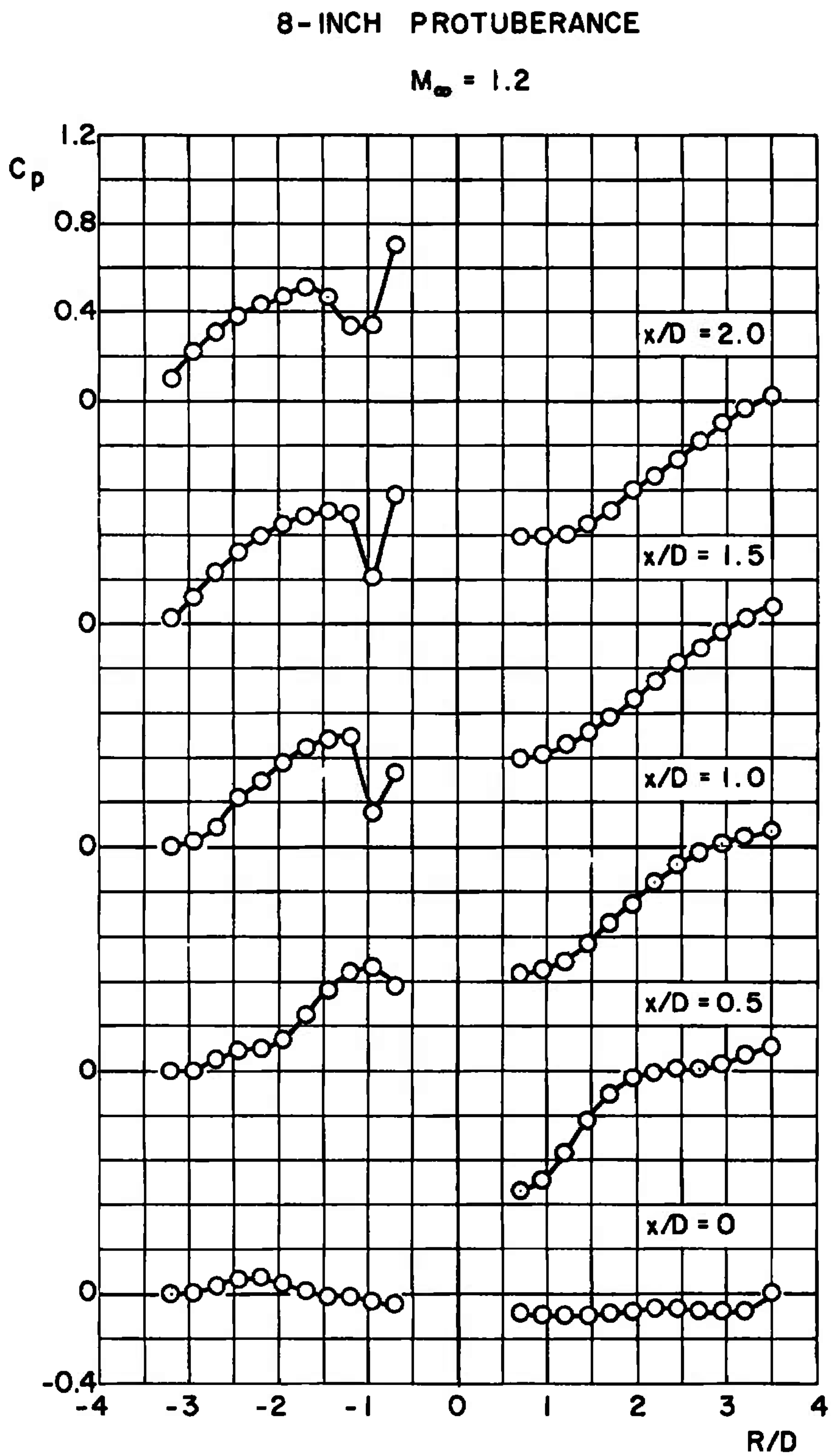


b. M_∞ = 0.80
Fig. 10 Continued

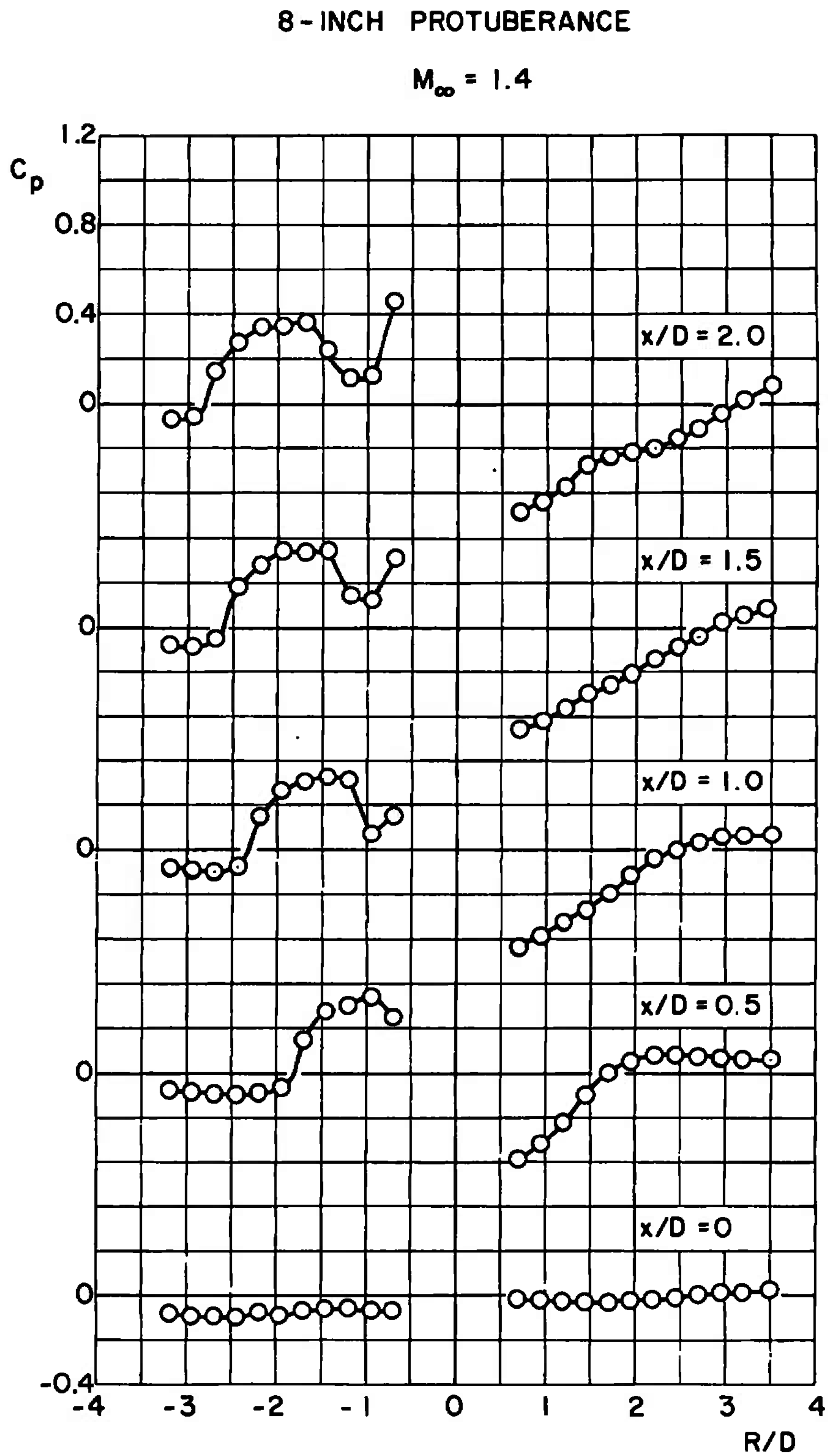


c. M_∞ = 1.00

Fig. 10 Continued

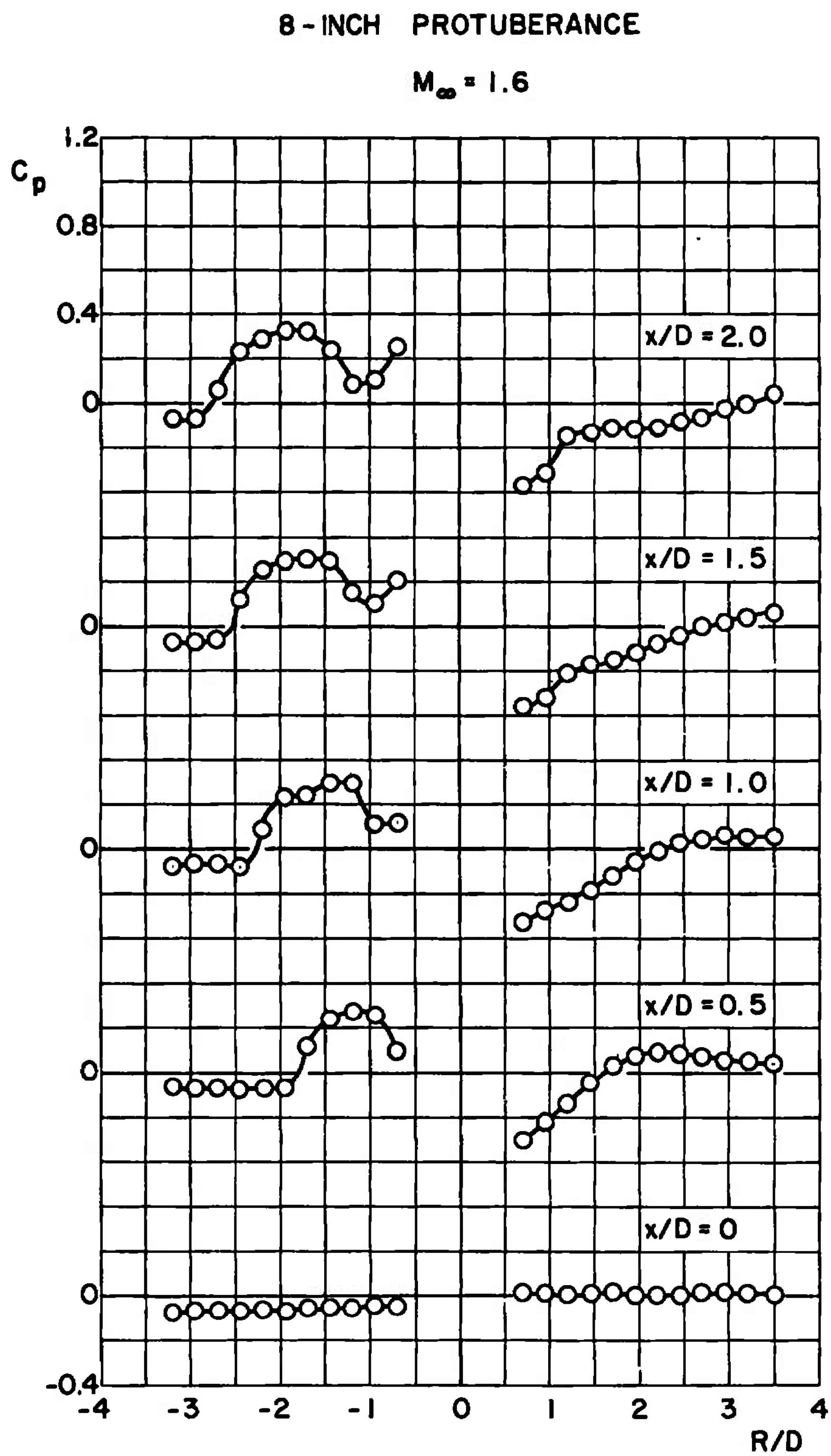


d. $M_\infty = 1.20$
Fig. 10 Continued

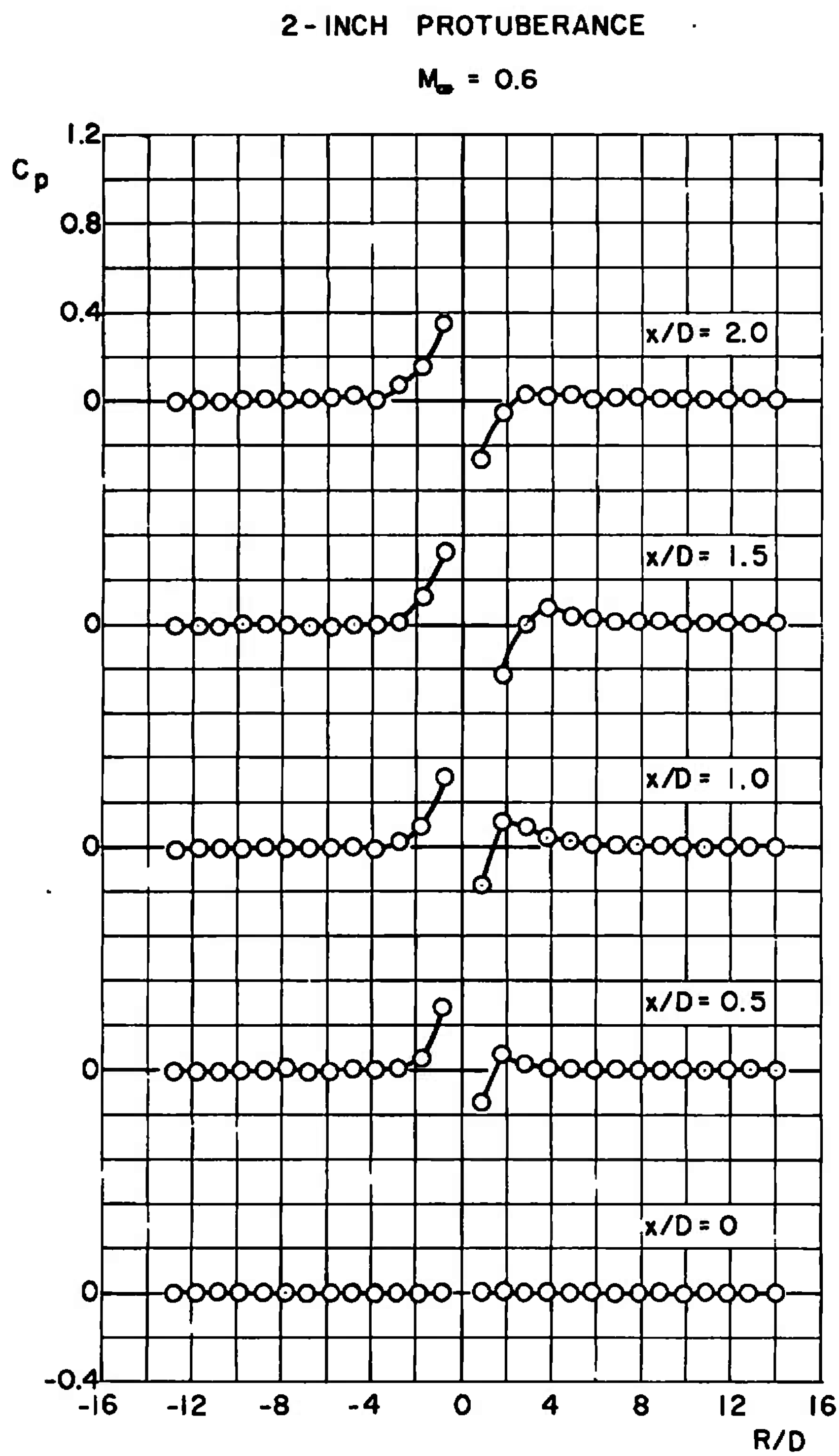


e. $M_\infty = 1.40$

Fig. 10 Continued

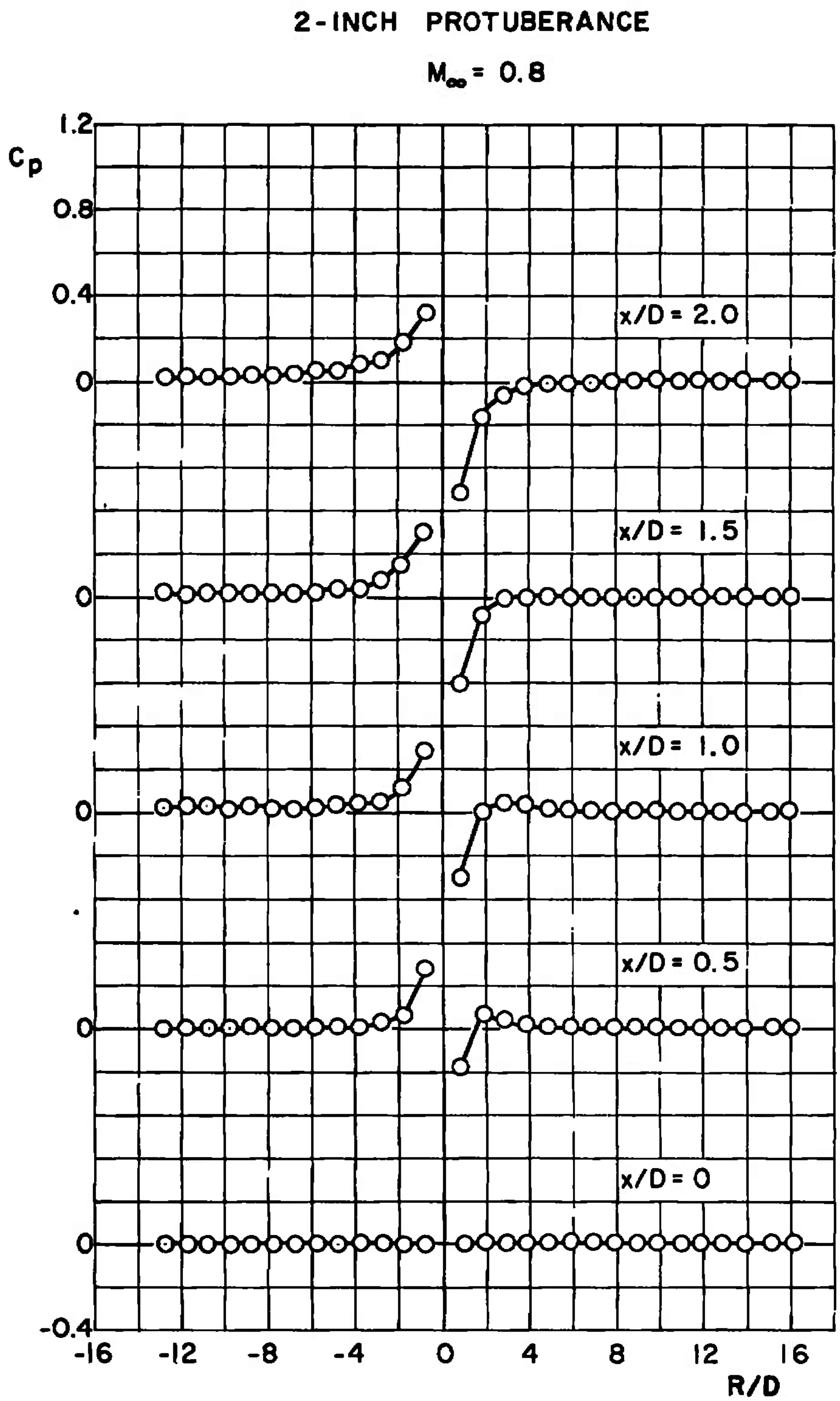


f. M_∞ = 1.60
Fig. 10 Concluded



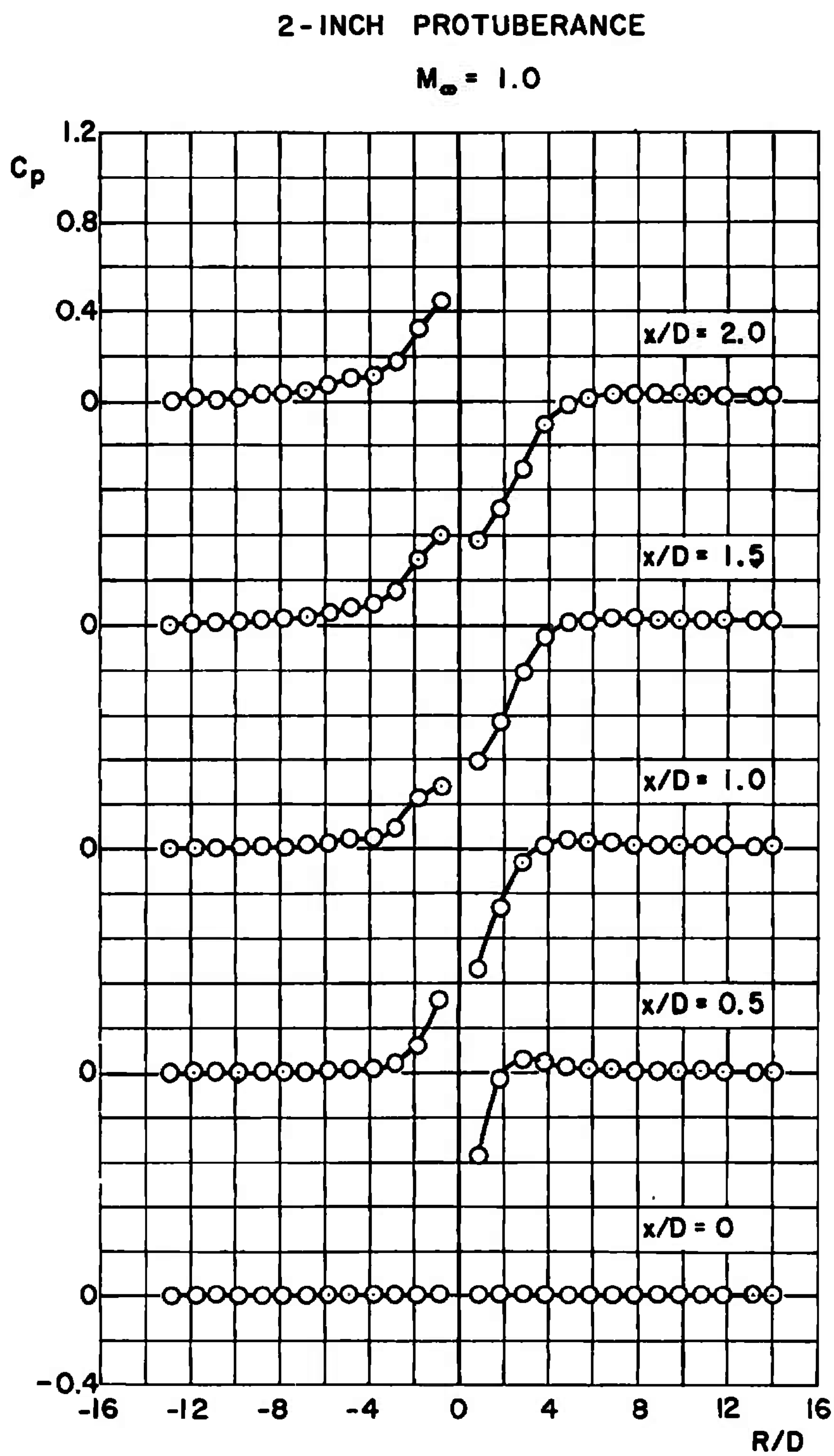
a. M_∞ = 0.60

Fig. 11 Variation of the Test Panel Centerline-Pressure Coefficients for the 2-in. Protuberance

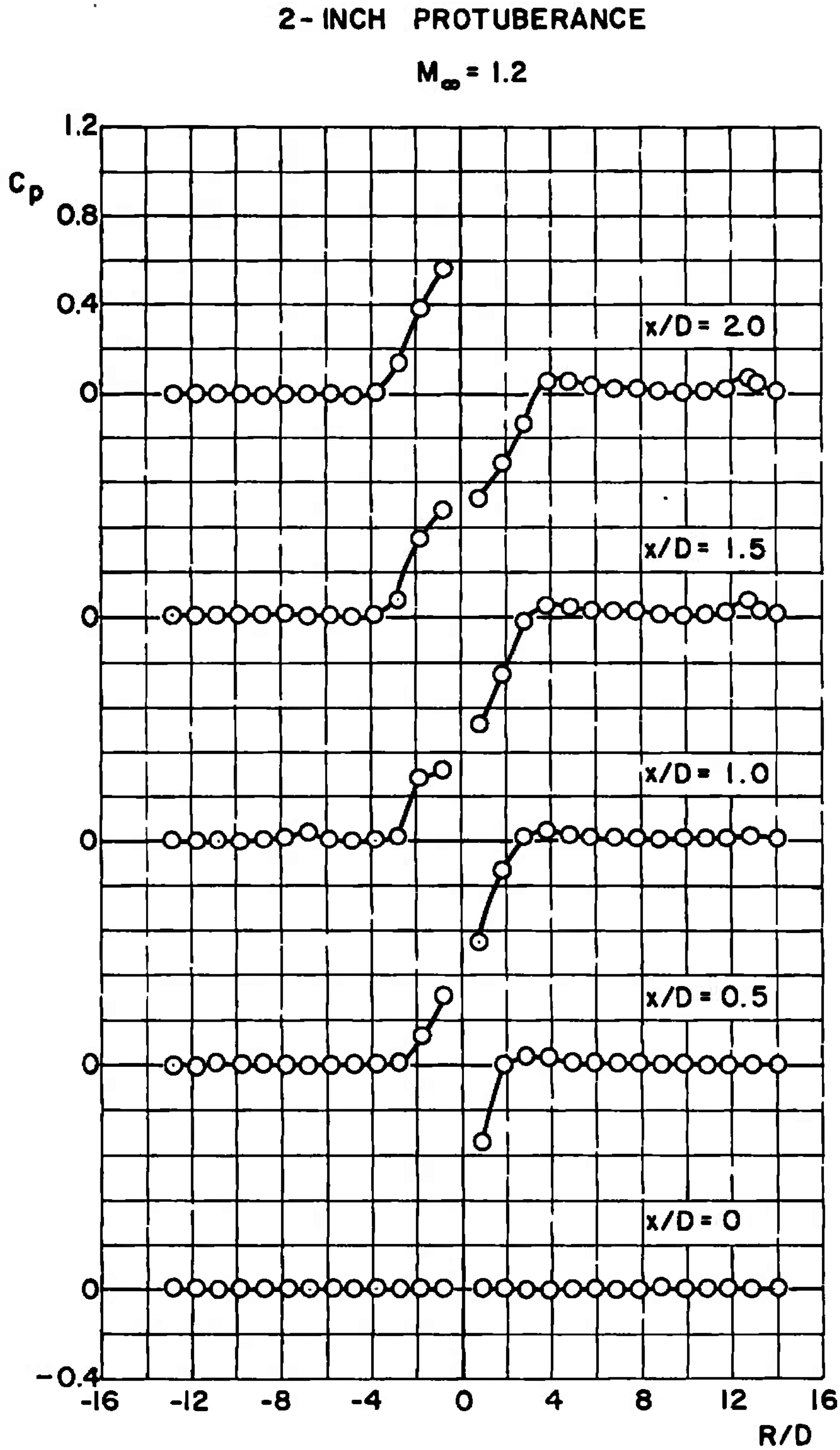


b. M_∞ = 0.80

Fig. 11 Continued

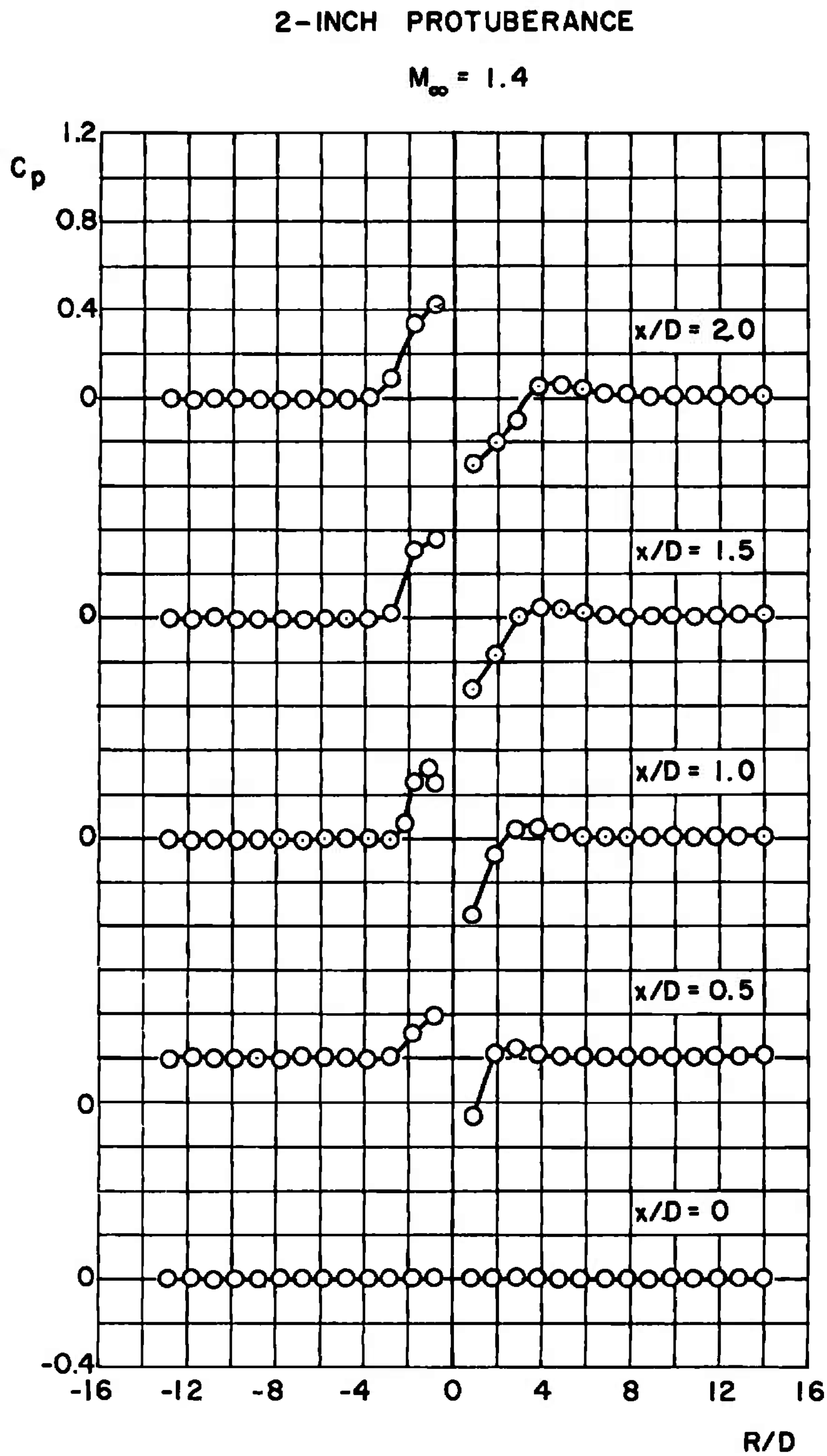


c. M_∞ = 1.00
Fig. 11 Continued

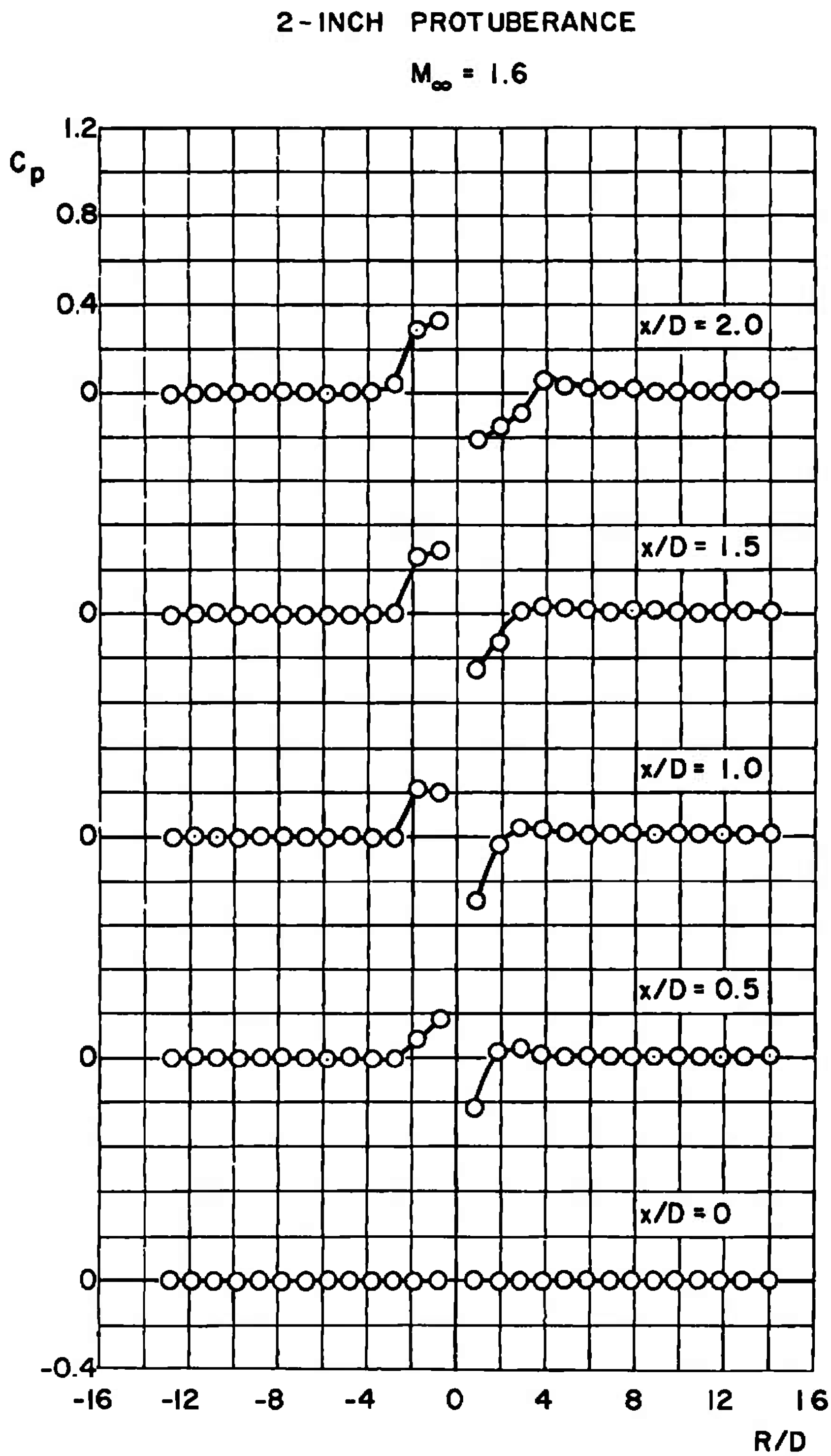


d. M_∞ = 1.20

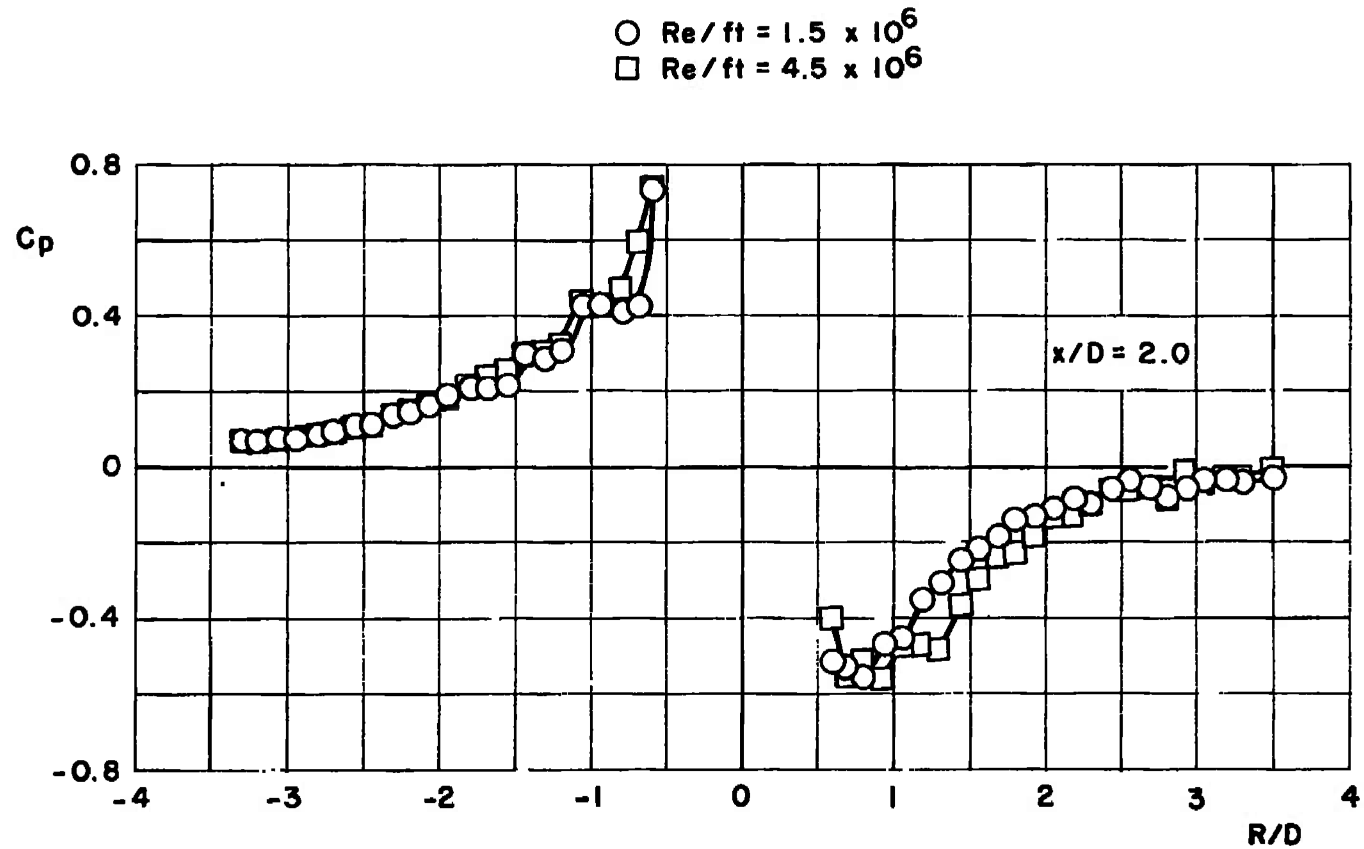
Fig. 11 Continued



e. M_∞ = 1.40
Fig. 11 Continued

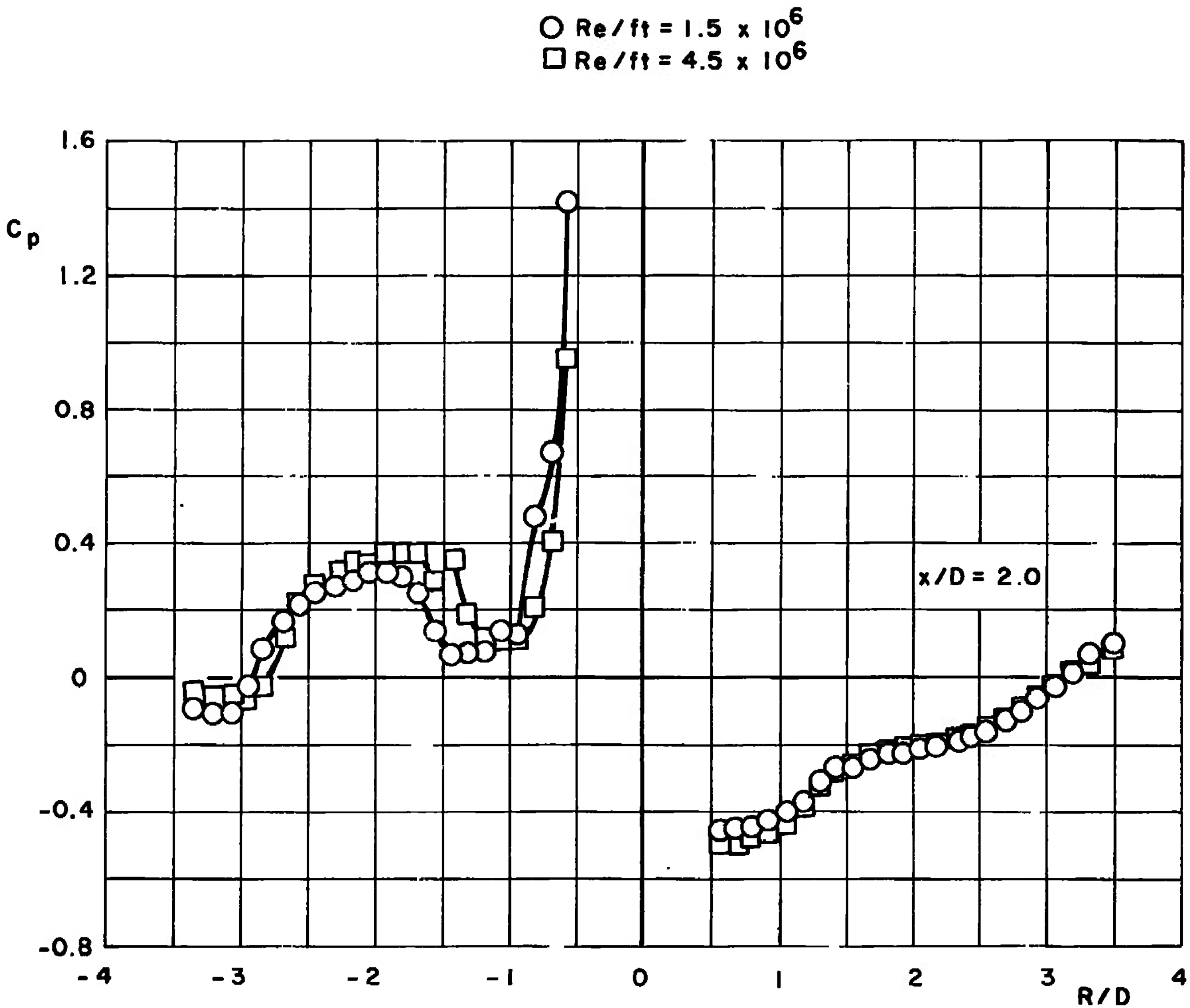


f. M_∞ = 1.60
Fig. 11 Concluded

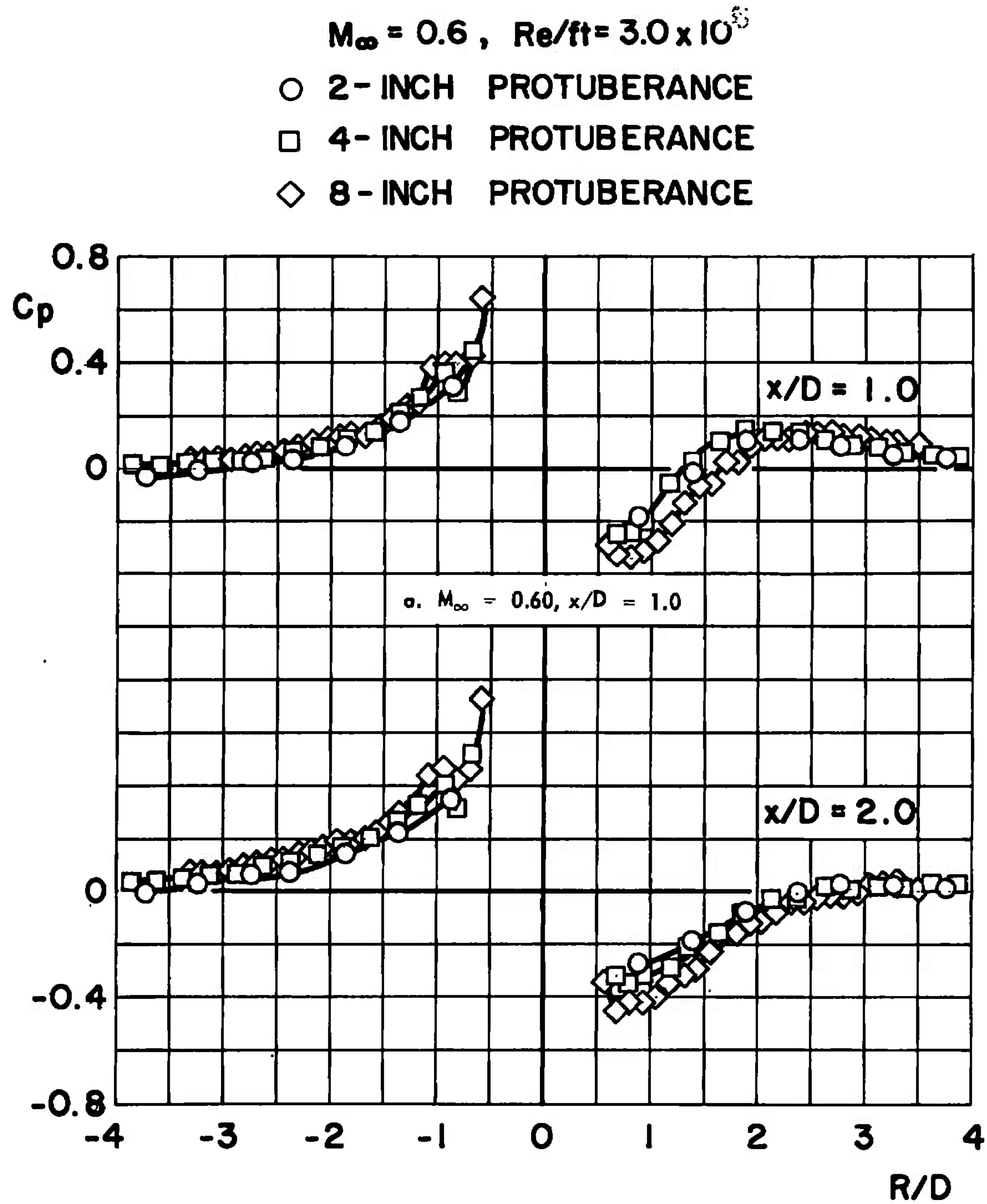


a. M_{∞} - 0.60

Fig. 12 Variation of the Test Panel Centerline-Pressure Coefficients for the 8-in. Protuberance at Two Reynolds Numbers

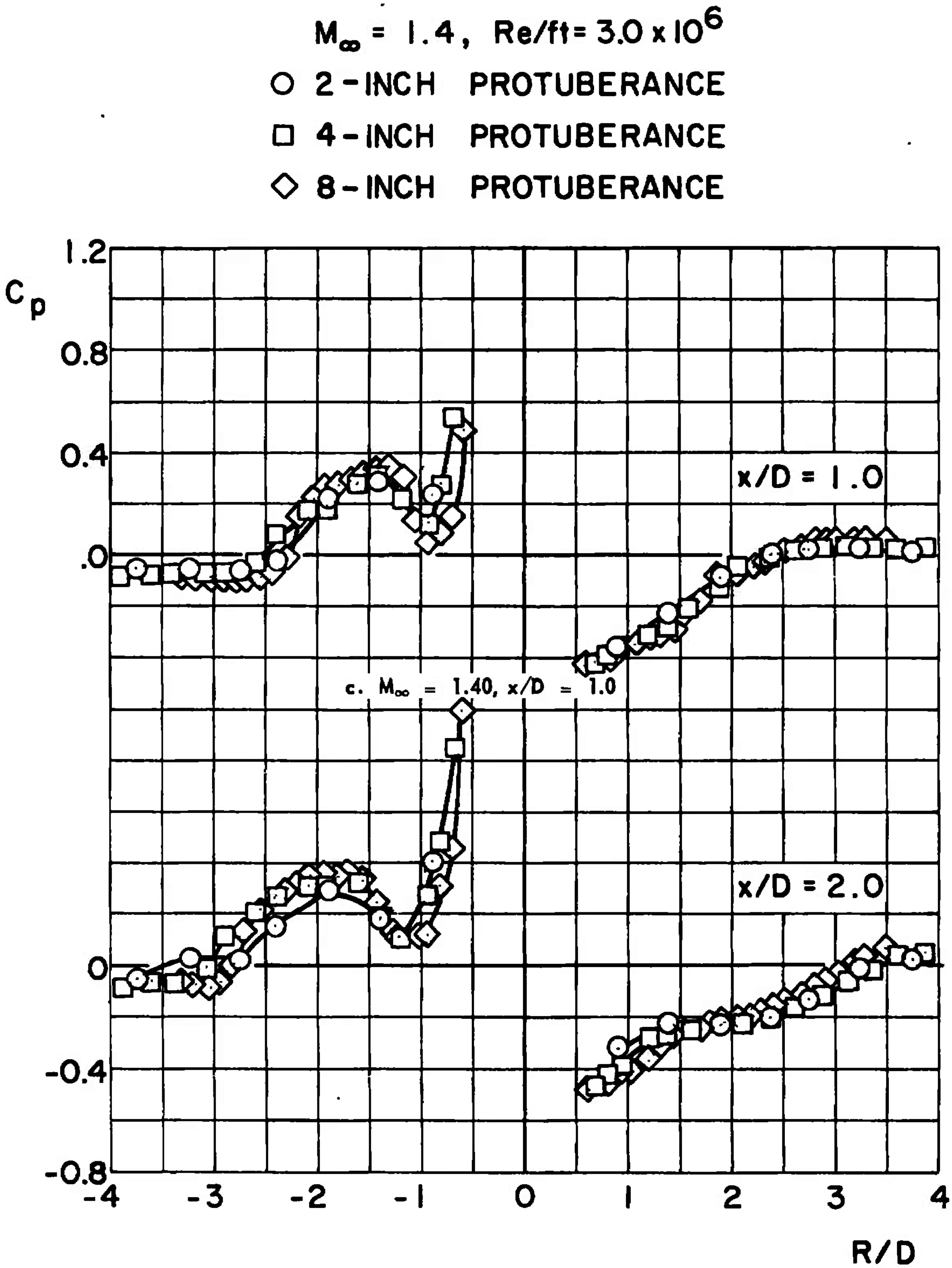


b. M_∞ = 1.40
Fig. 12 Concluded



b. $M_\infty = 0.60$, $x/D = 2.0$

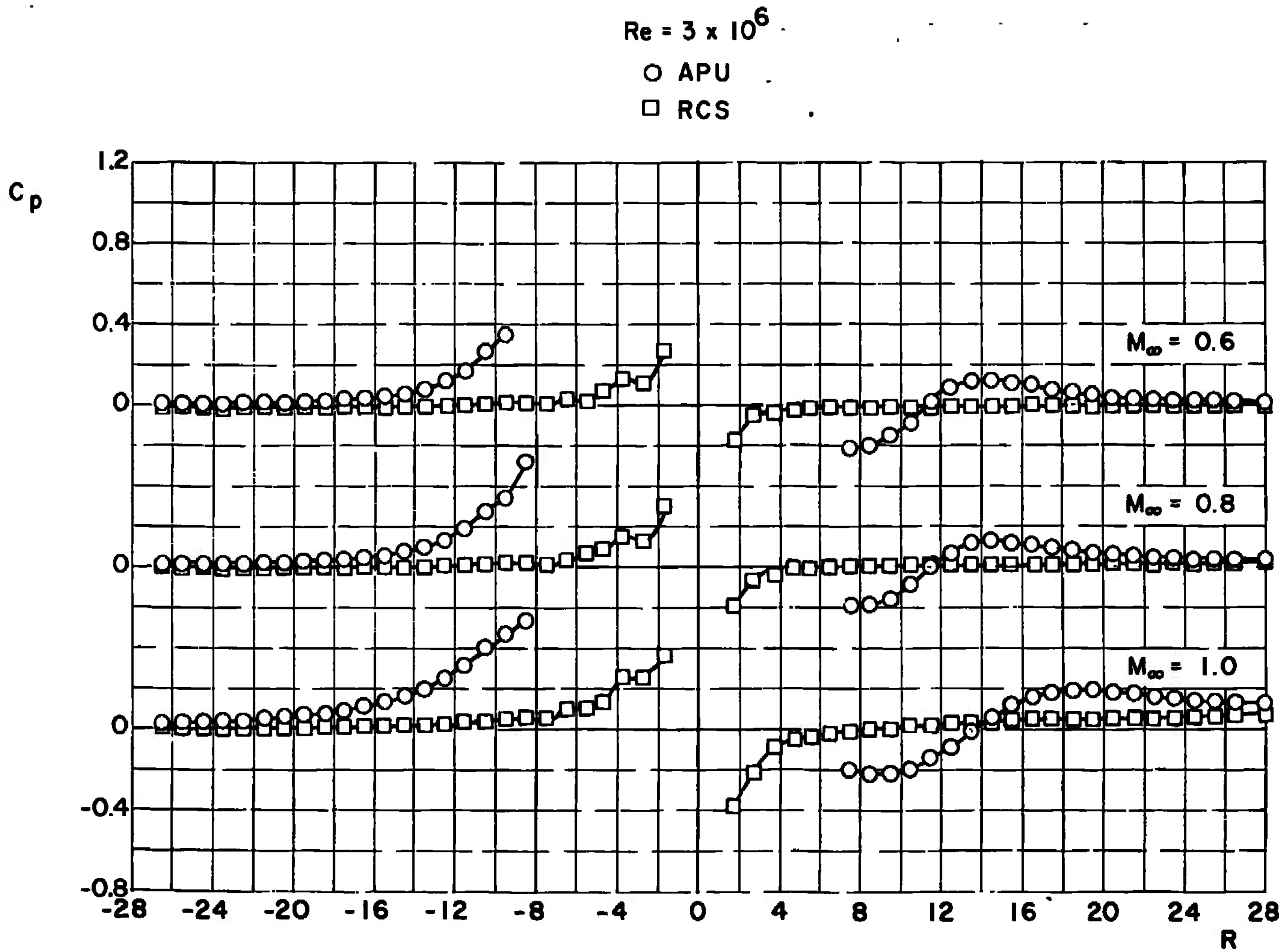
Fig. 13 Variation of the Test Panel Centerline-Pressure Coefficients for Three Protuberances at $Re/ft = 3.0 \times 10^6$



c. M_∞ = 1.40, x/D = 1.0

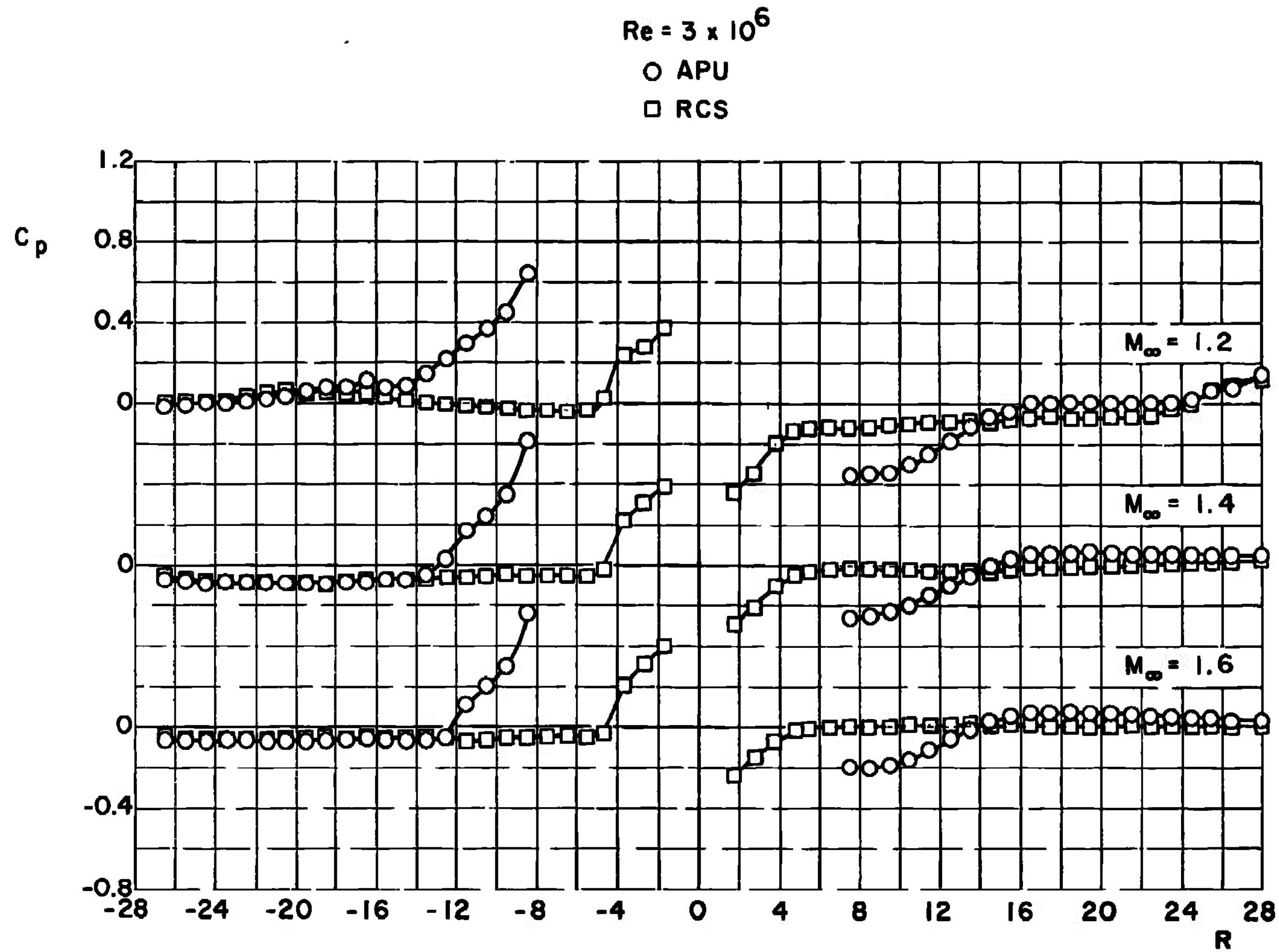
d. M_∞ = 1.40, x/D = 2.0

Fig. 13 Concluded

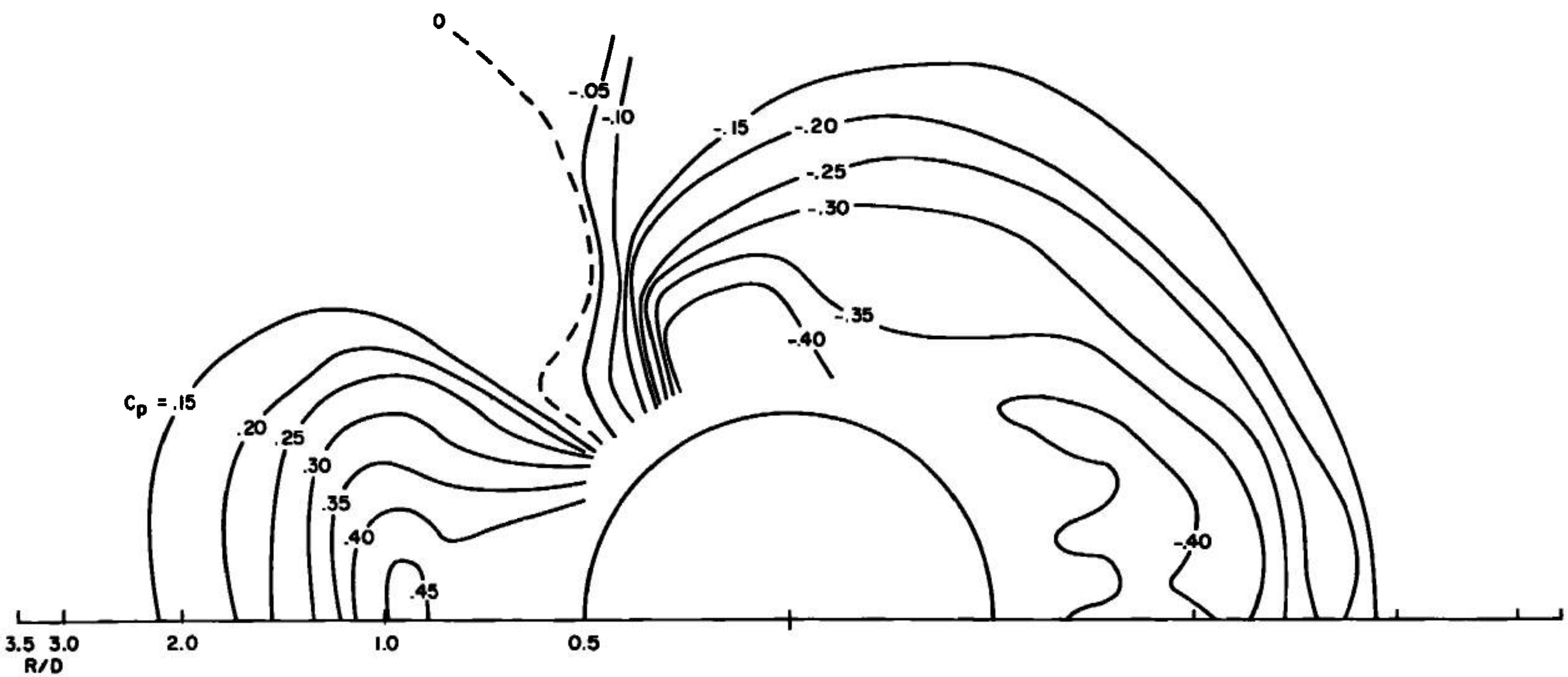


a. M_∞ = 0.60 through 1.00

Fig. 14 Variation of the Test Panel Centerline-Pressure Coefficients for the Auxiliary Propulsion Unit and Rocket Control System Protuberances, Re/ft = 3.0×10^6

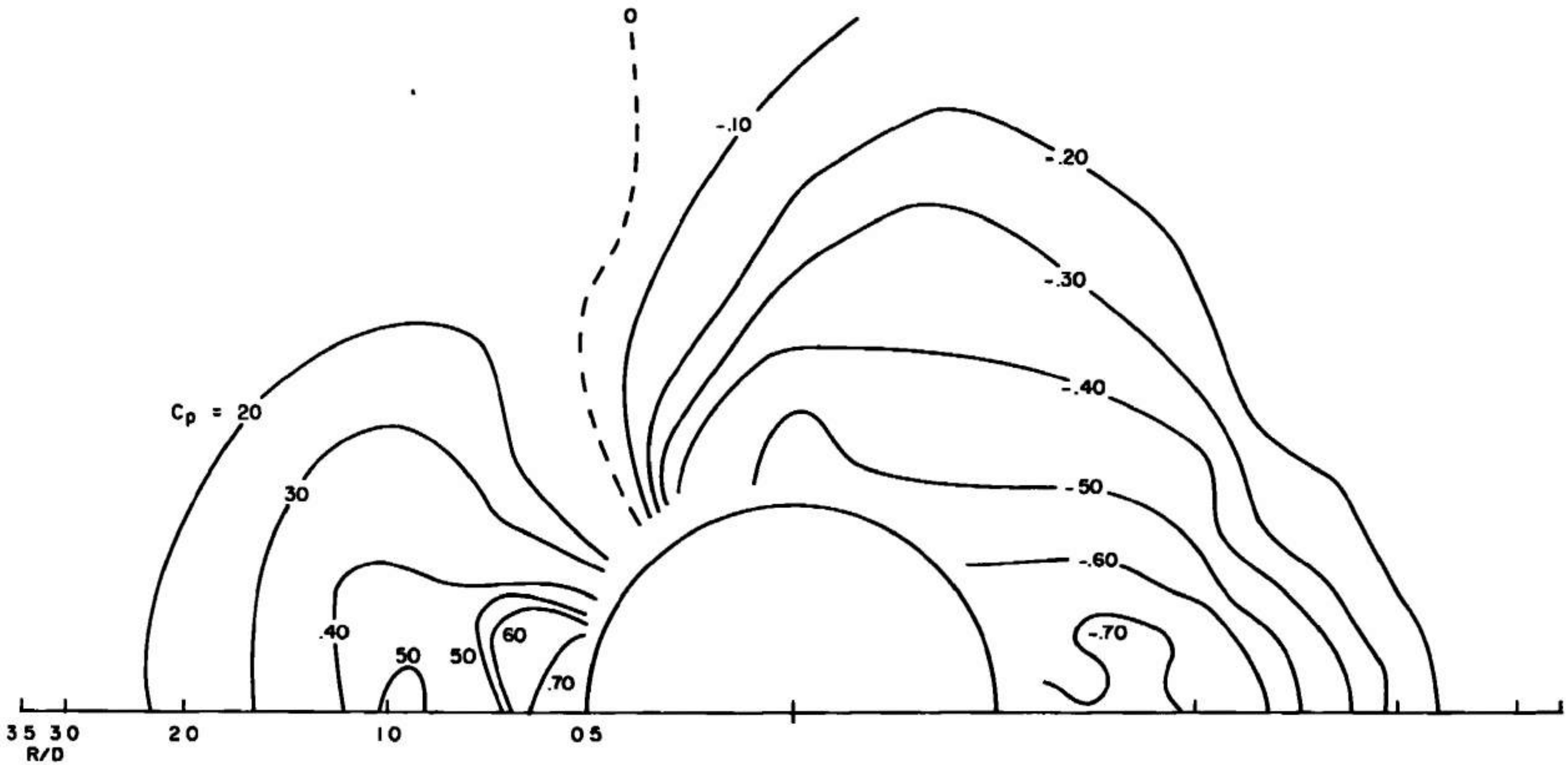


b. M_∞ = 1.20 through 1.60
Fig. 14 Concluded



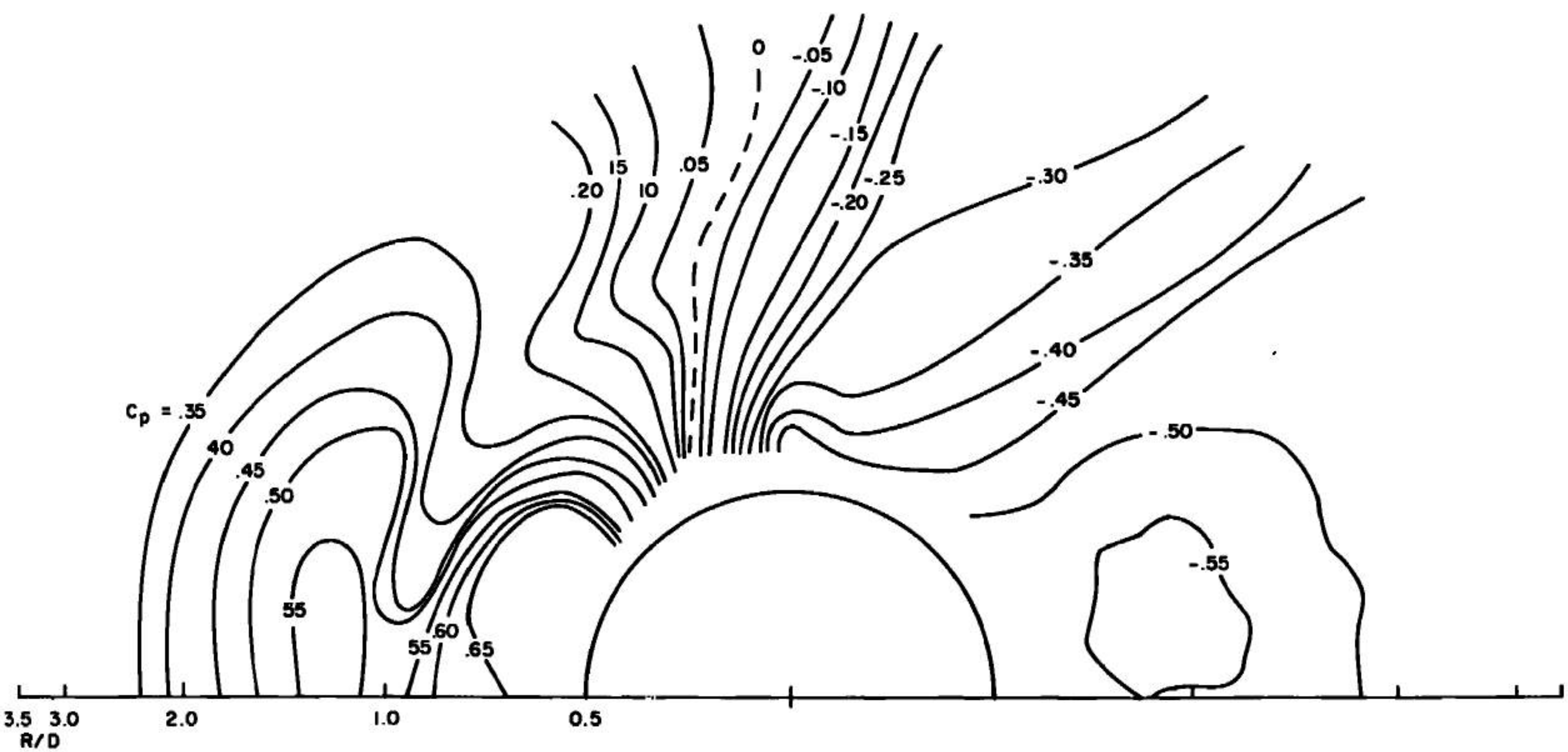
a. M_∞ = 0.60

Fig. 15 Pressure-Coefficient Isolines on the Test Panel about the 8-in. Protuberance, x/D = 2.00

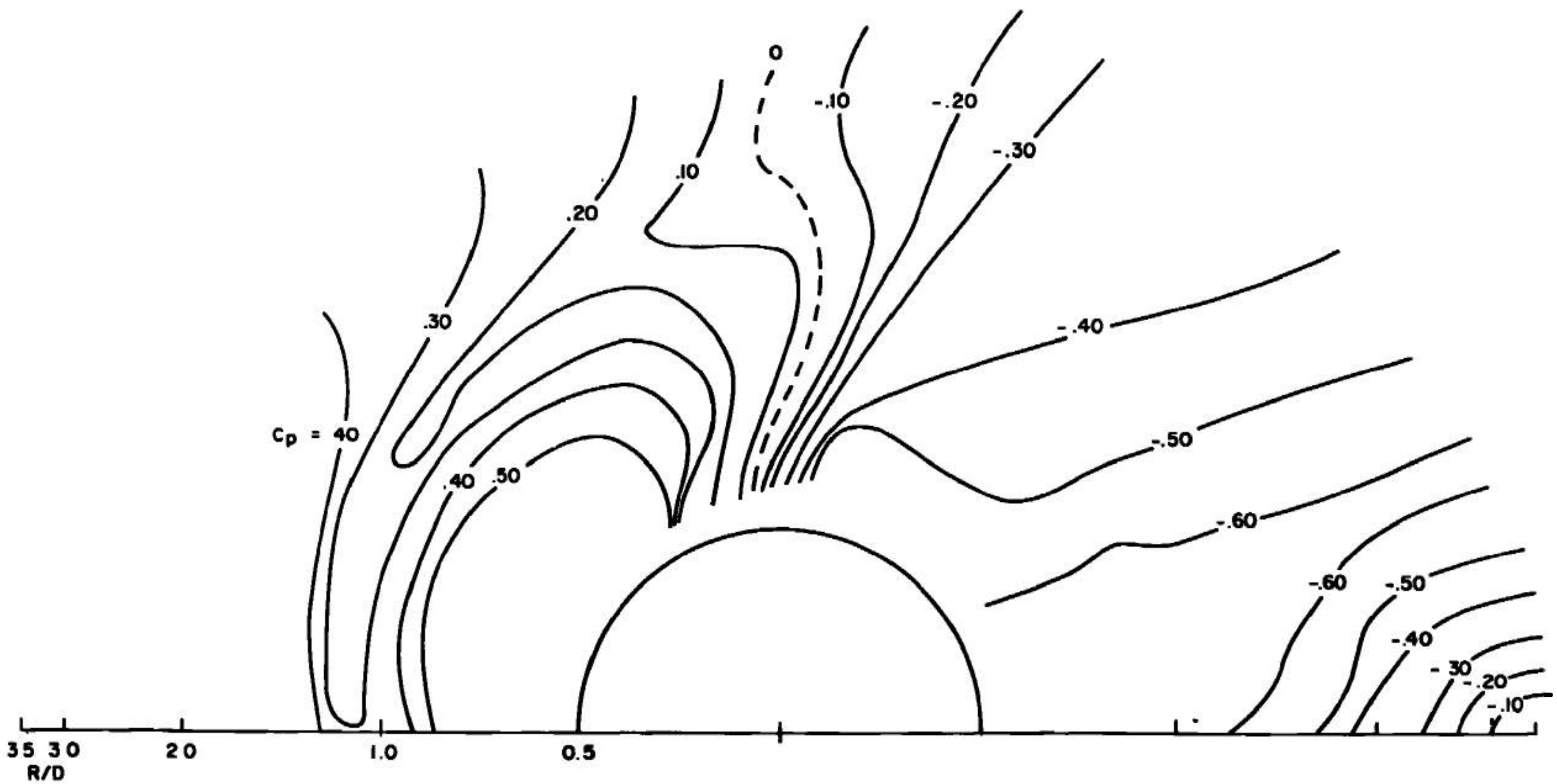


b. M_{∞} = 0.80

Fig. 15 Continued

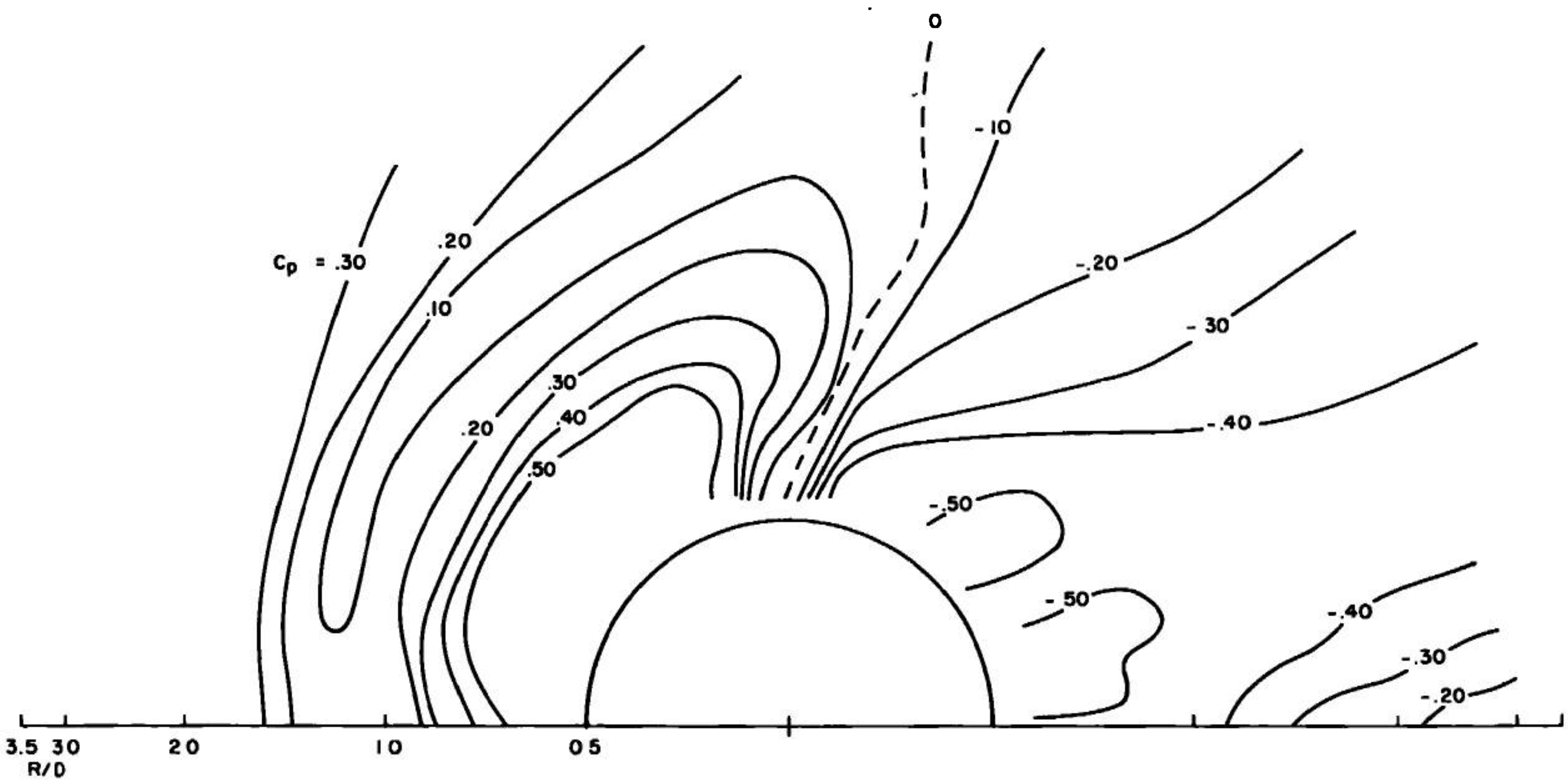


c. M_∞ = 1.00
Fig. 15 Continued



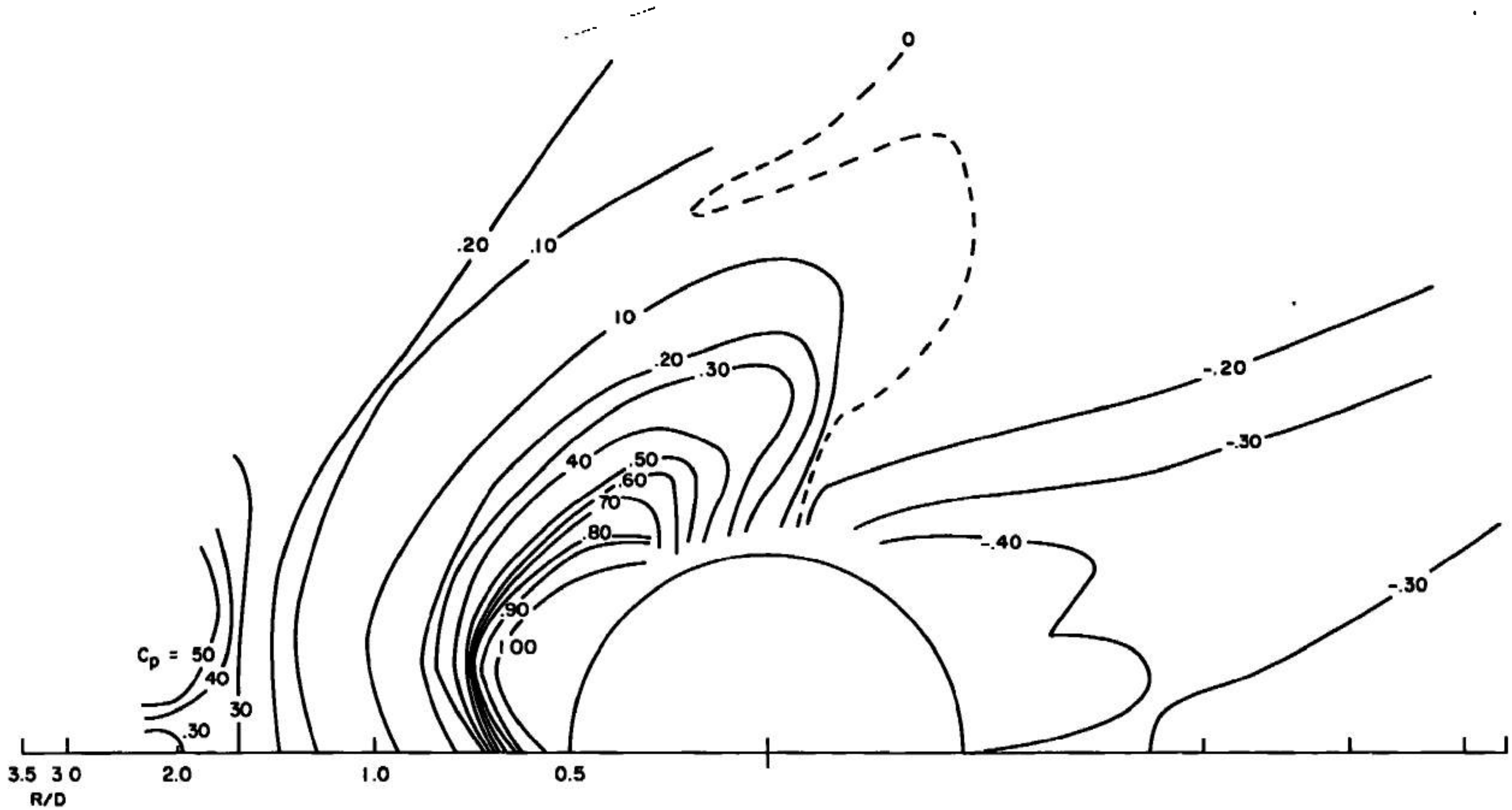
d. M_∞ = 1.20

Fig. 15 Continued



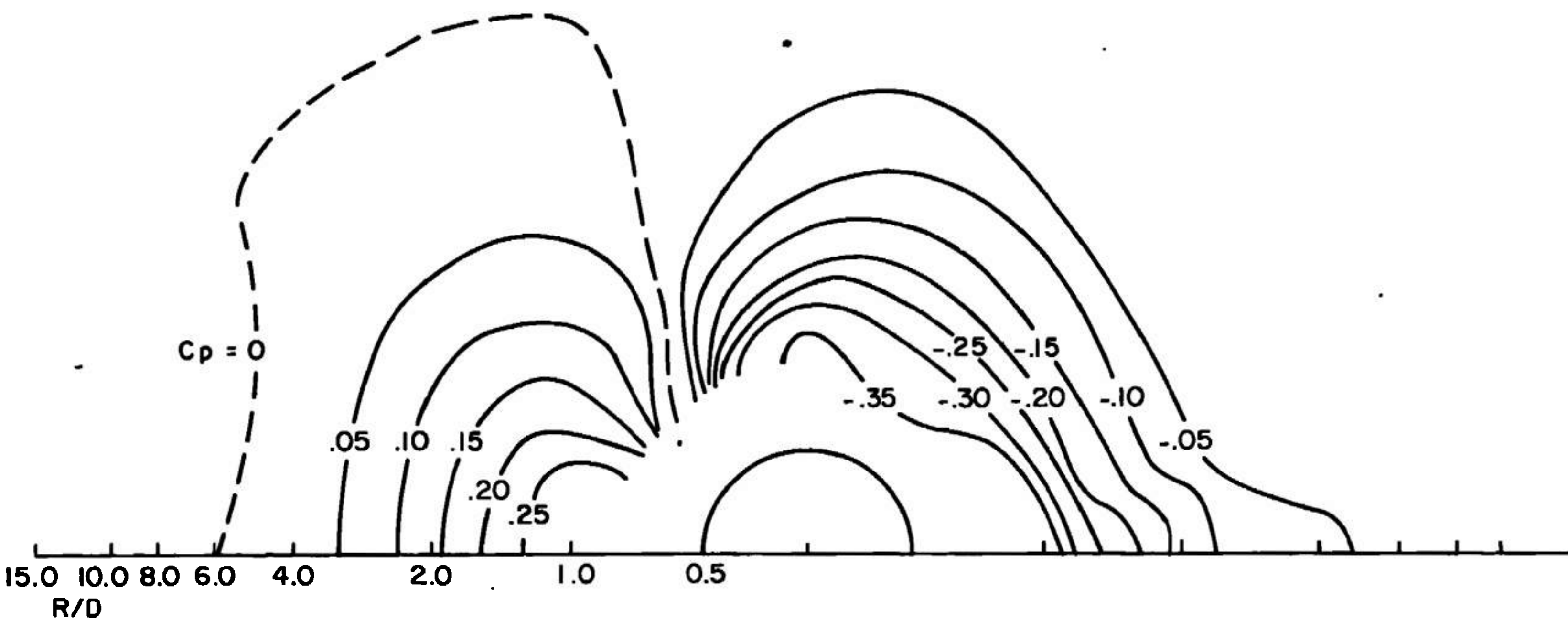
e. M_∞ = 1.40

Fig. 15 Continued



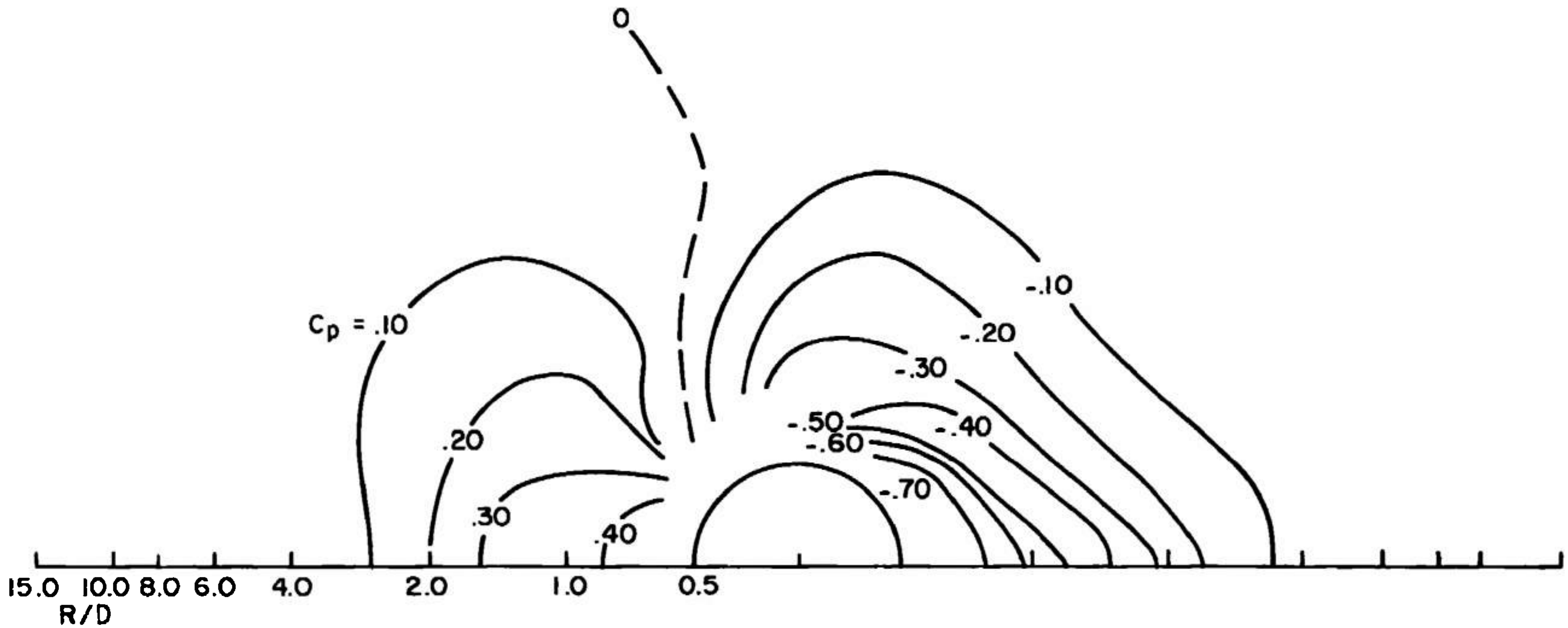
f. M_∞ = 1.60

Fig. 15 Concluded

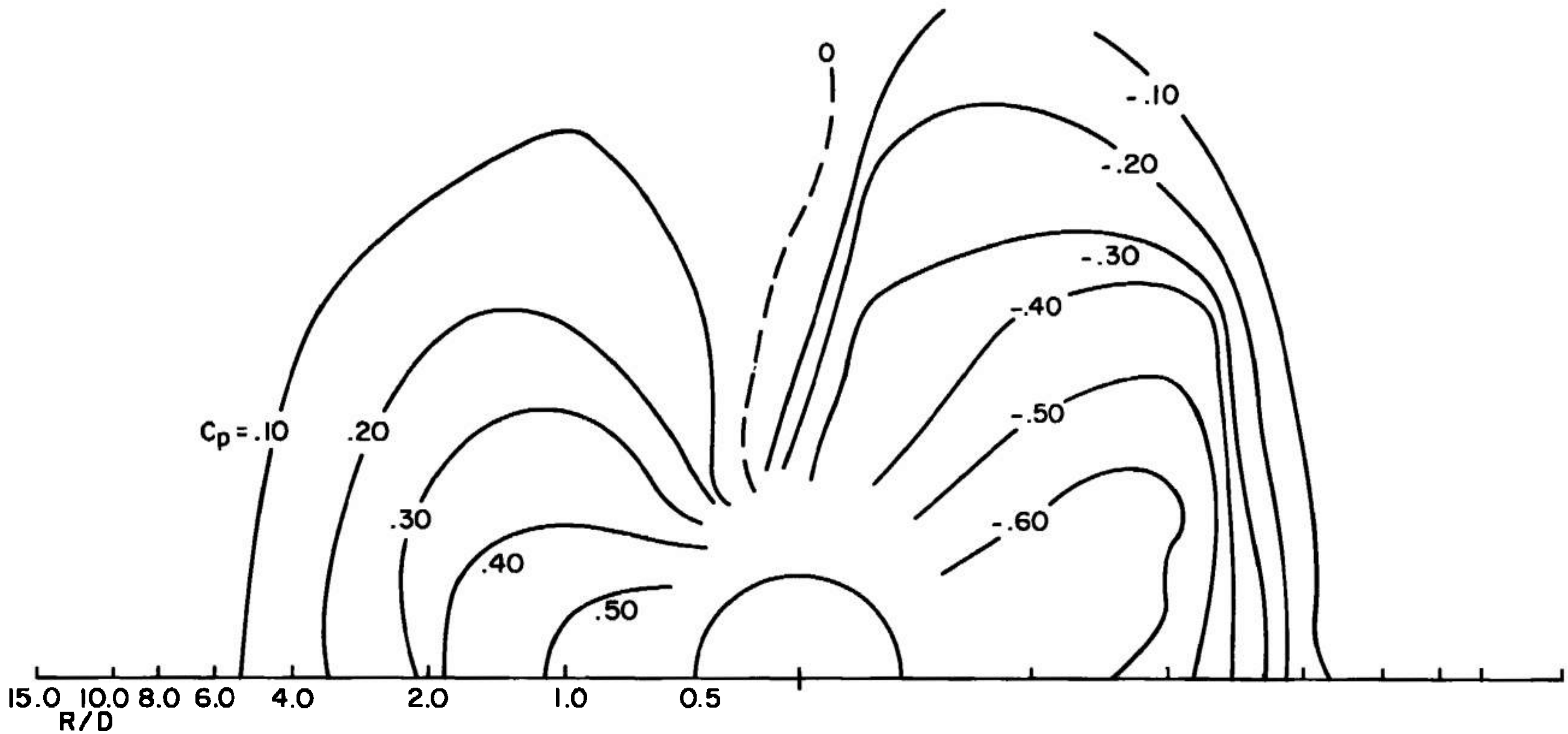


a. $M_\infty = 0.60$

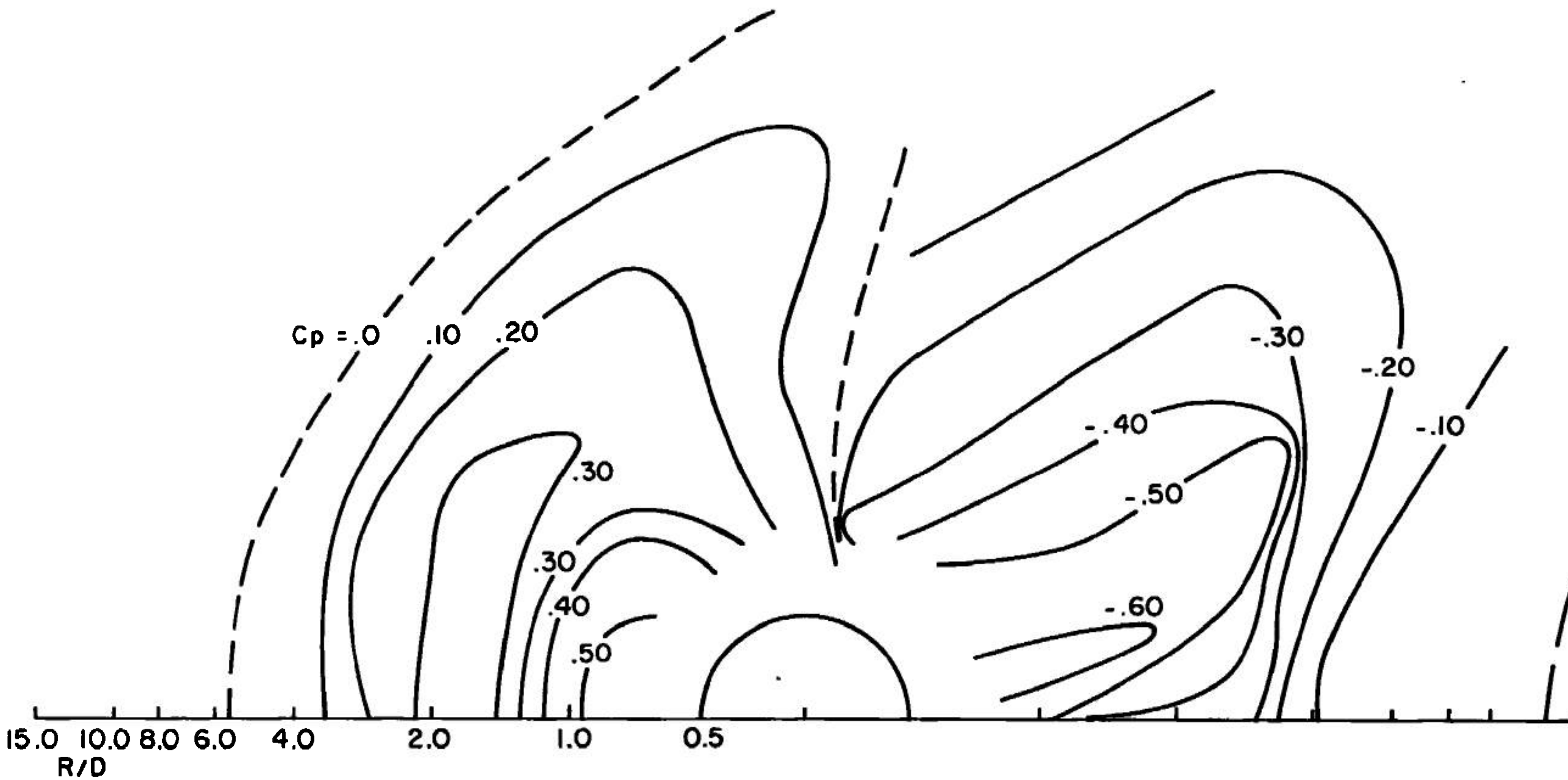
Fig. 16 Pressure-Coefficient Isolines on the Test Panel about the 2-in. Protuberance, x/D = 3.00



b. M_∞ = 0.80
Fig. 16 Continued

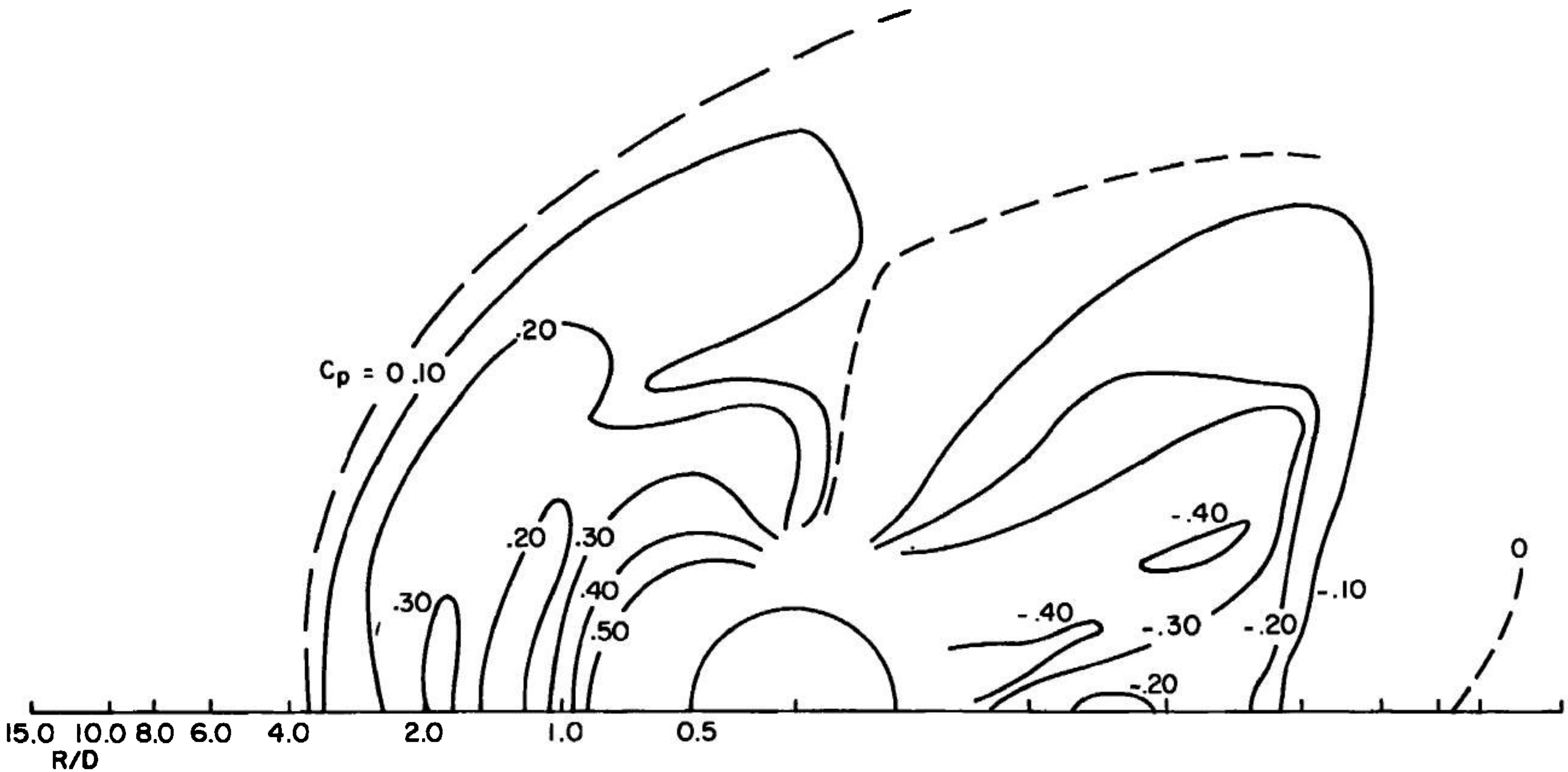


c. $M_\infty = 1.00$
Fig. 16 Continued



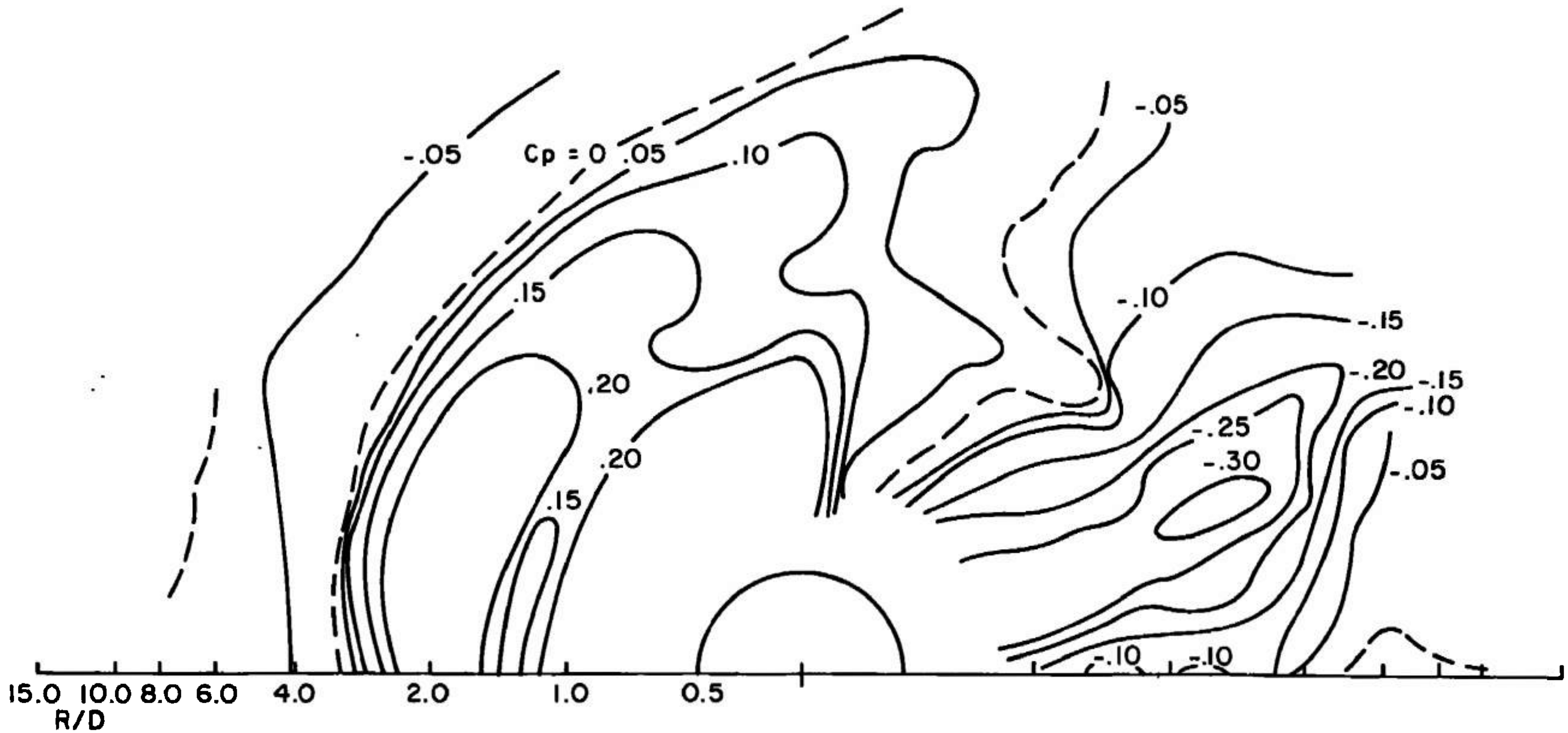
d. M_∞ 1.20

Fig. 16 Continued

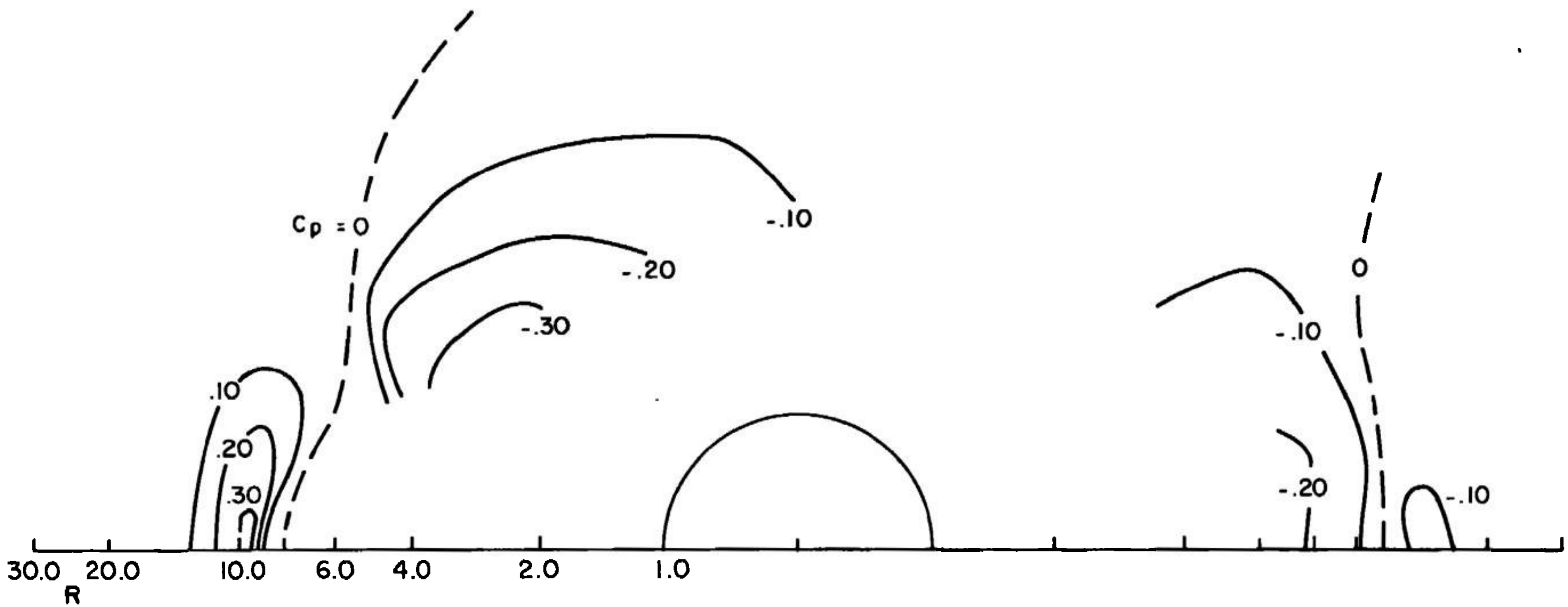


e. $M_\infty = 1.40$

Fig. 16 Continued

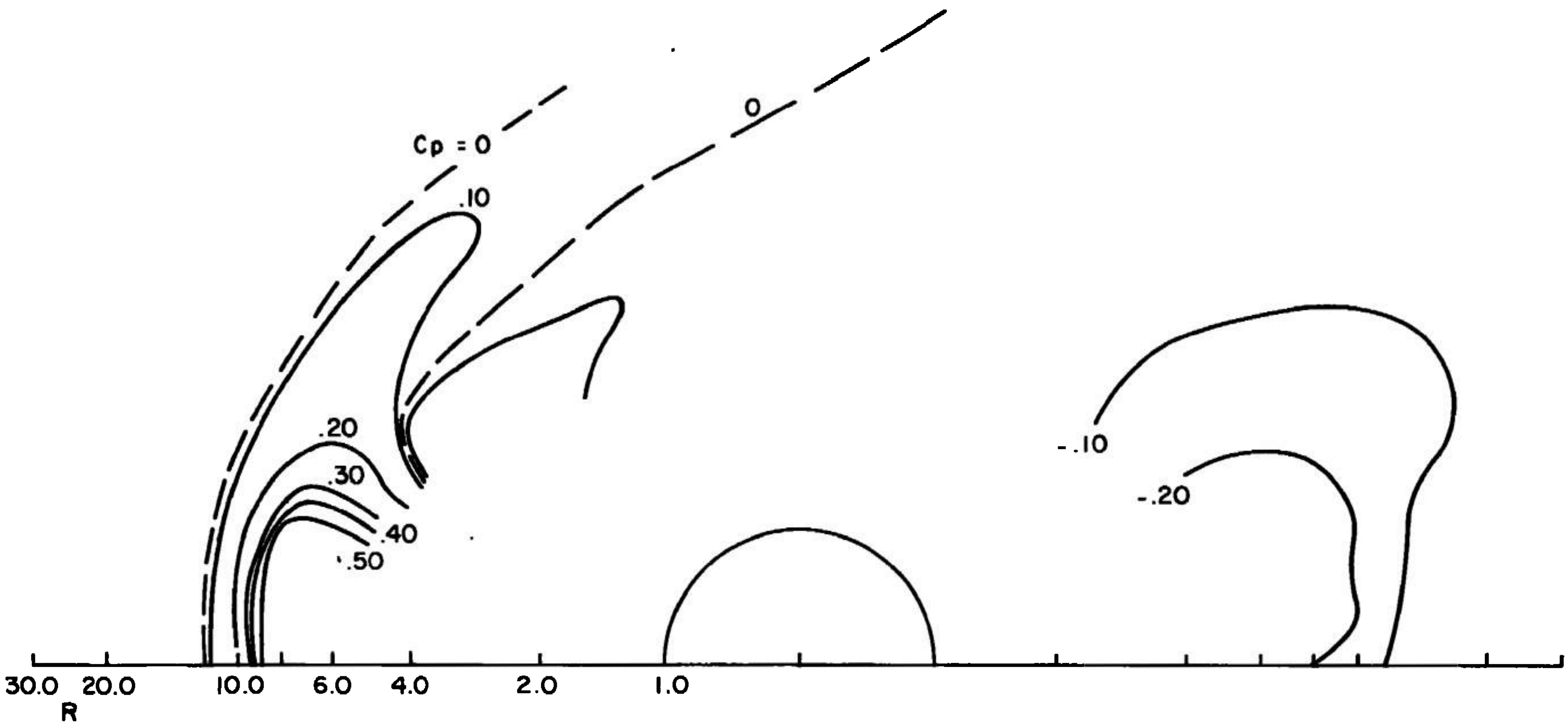


f. M_∞ = 1.60
Fig. 16 Concluded

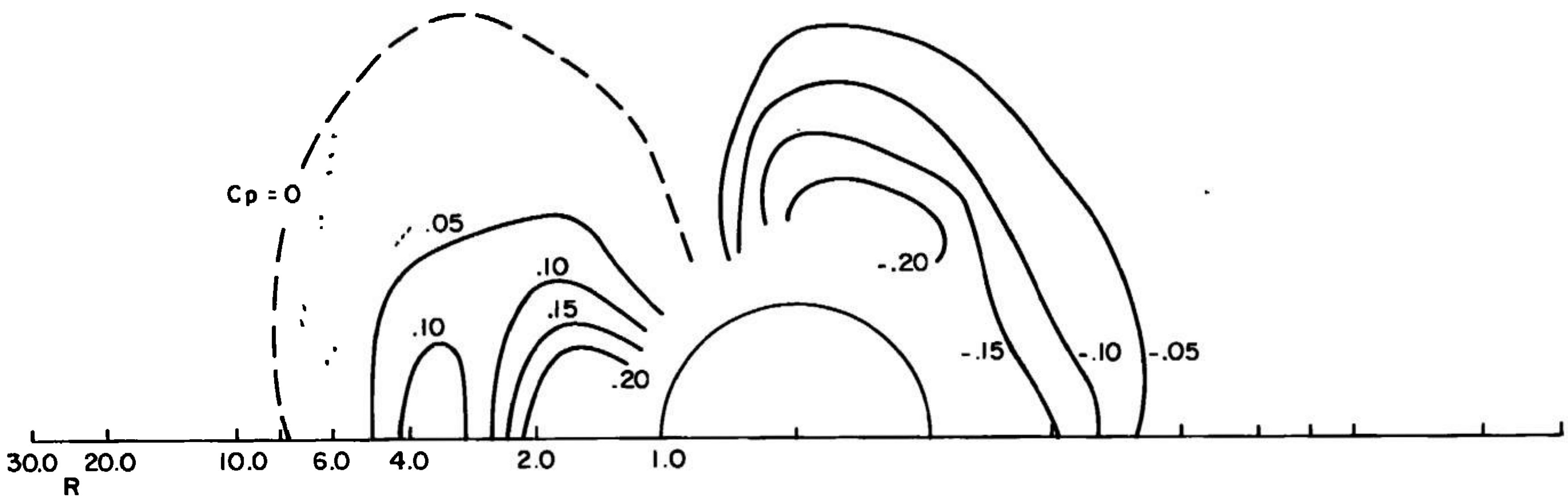


a. $M_\infty = 0.60$

Fig. 17 Pressure Coefficient Isolines for the Auxiliary Propulsion Unit, $Re/ft = 3.0 \times 10^6$

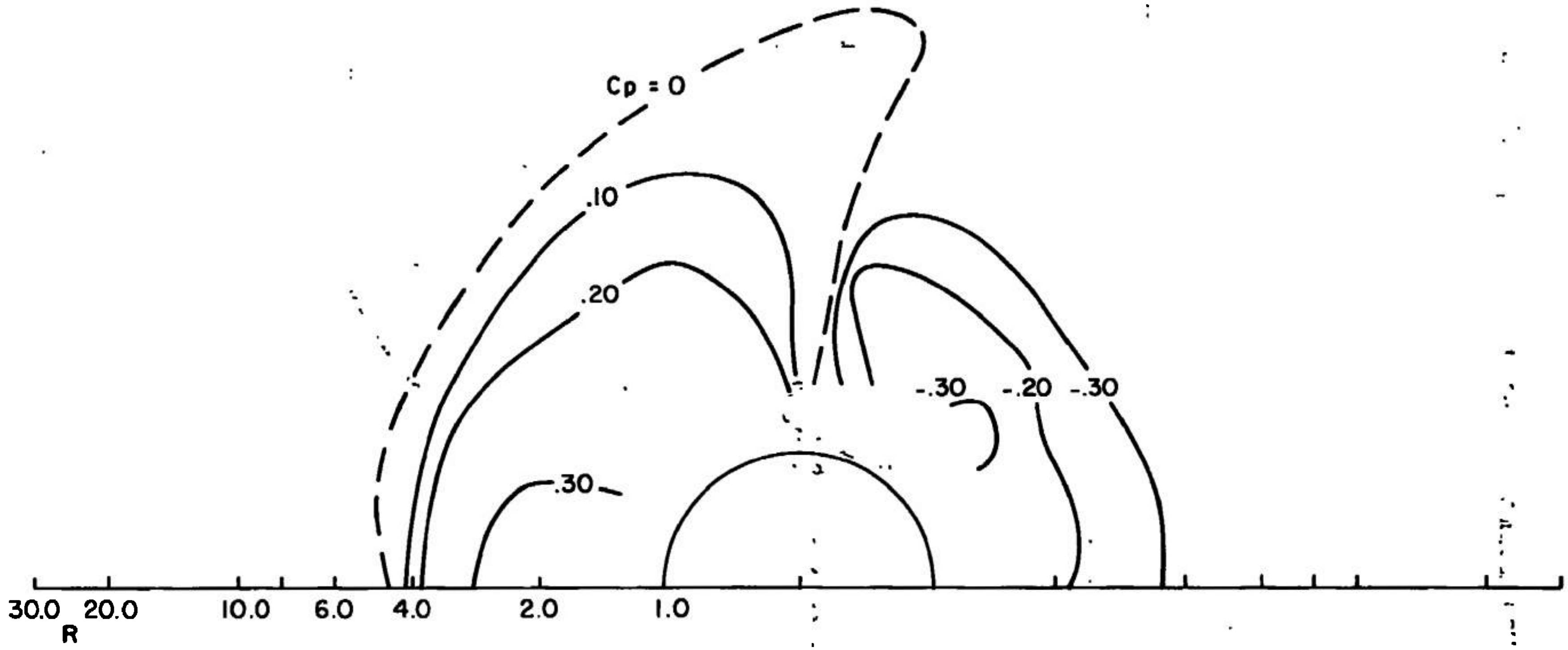


b. $M_\infty = 1.60$
Fig. 17 Concluded



a. $M_\infty = 0.60$

Fig. 18 Pressure Coefficient Isolines for the Rocket Control System, $Re/ft = 3.0 \times 10^6$



b. $M_\infty = 1.60$

Fig. 18 Concluded

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13. ABSTRACT

Generalized protuberances in the form of right circular cylinders of 2-, 4-, and 8-in. diameter were mounted on a full-scale Saturn S-IVB panel and tested at various heights for Mach numbers 0.60 through 1.60. Models of the Auxiliary Propulsion Unit and the Rocket Control System protuberances of the Saturn V launch vehicle were also tested. The Reynolds number based on the generalized protuberance diameters varied from 0.25 to 3.0 million. Static and fluctuating pressure levels in the regions around the protuberances were determined, and flow visualization studies were also made. The fluctuating pressure and flow visualization data are not presented in this report.

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cylinders						
wind tunnel tests						
transonic flow						
flow visualization						
2. Protuberance -- Flow visualization						
3 " -- Flow field						
4 " -- Pressure distribution						
5 Stores -- Transonic flow						
6 " -- Flow fields						
1 - 2						